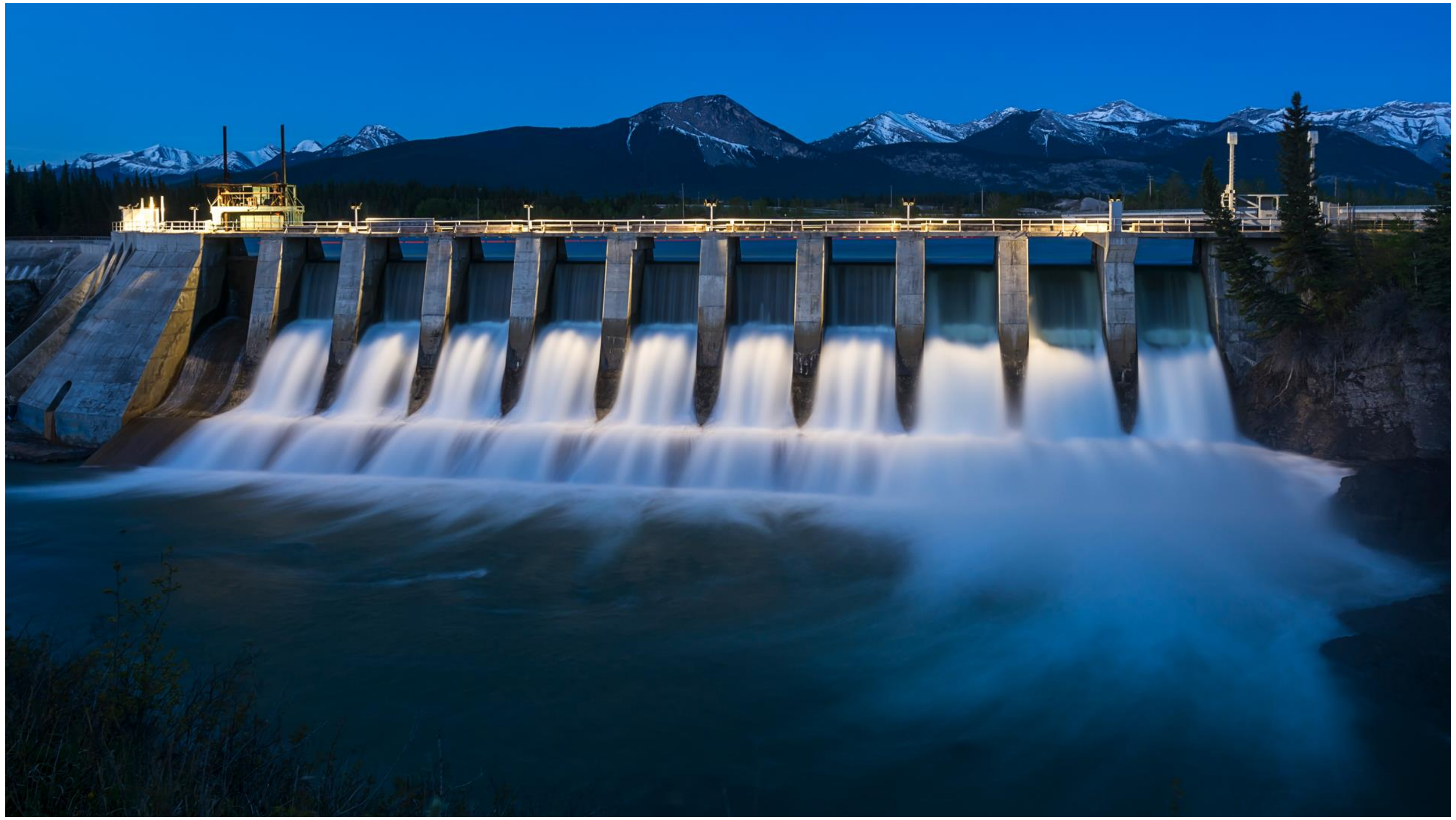
Hydropower

Lecture 2



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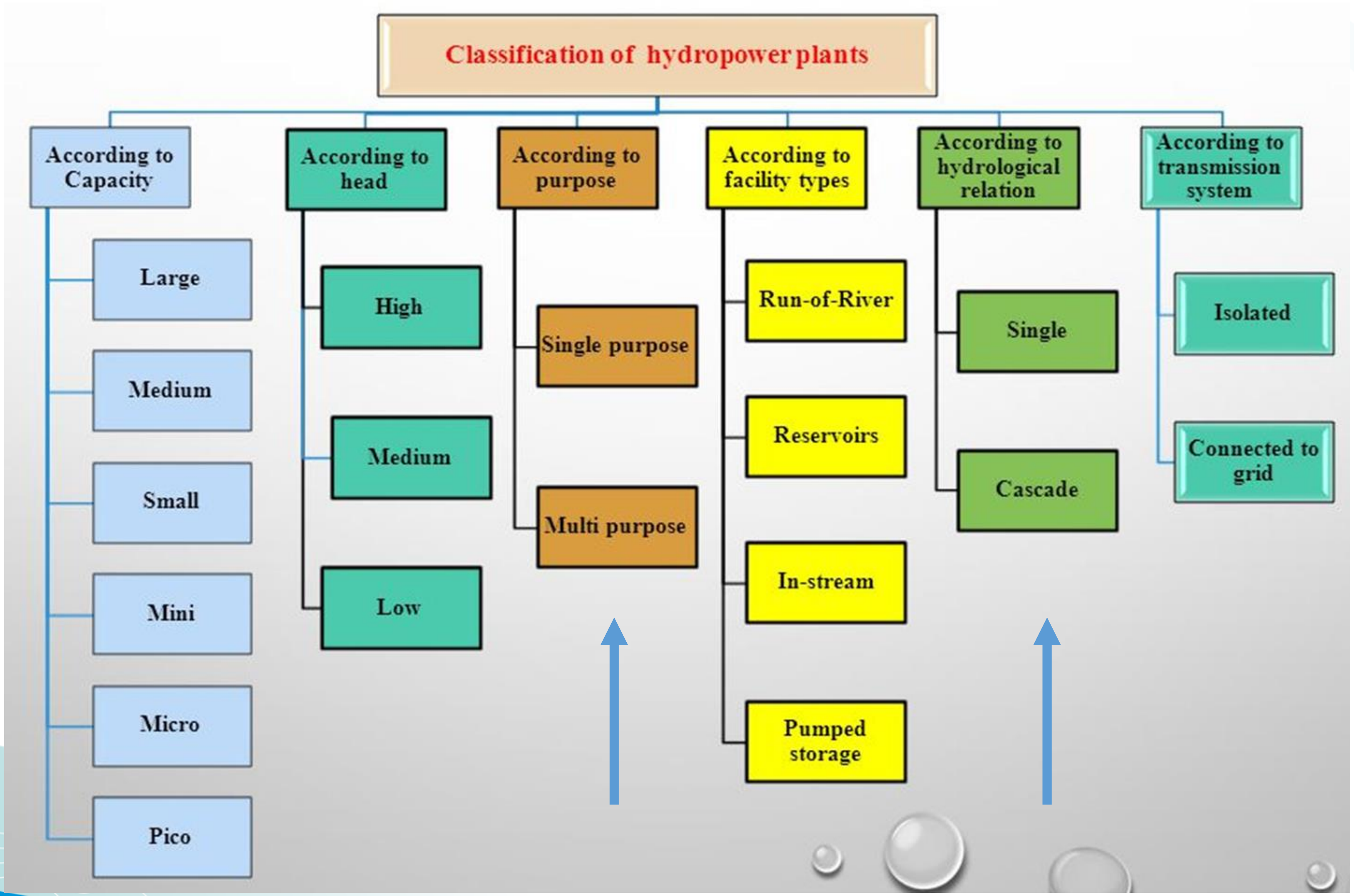
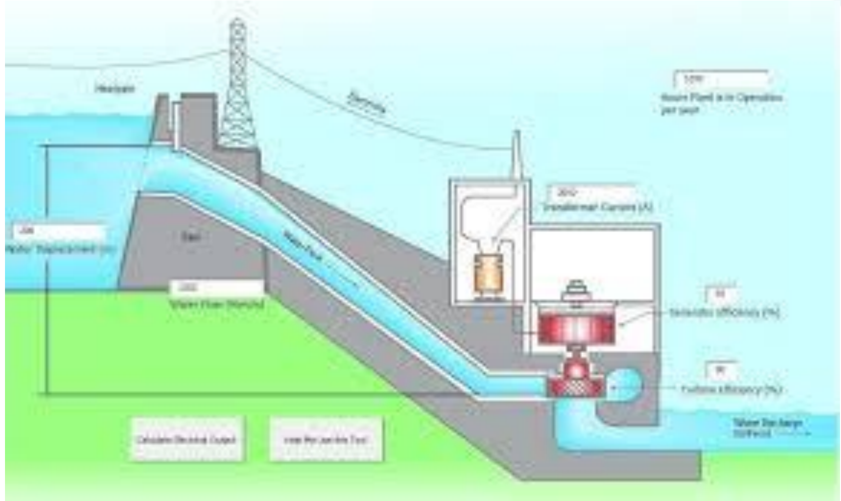
Classification



Source: https://slideplayer.com/slide/9289734/

Classification according to purpose

Single purpose:
When the purpose of the hydropower plant is only to produce electricity.



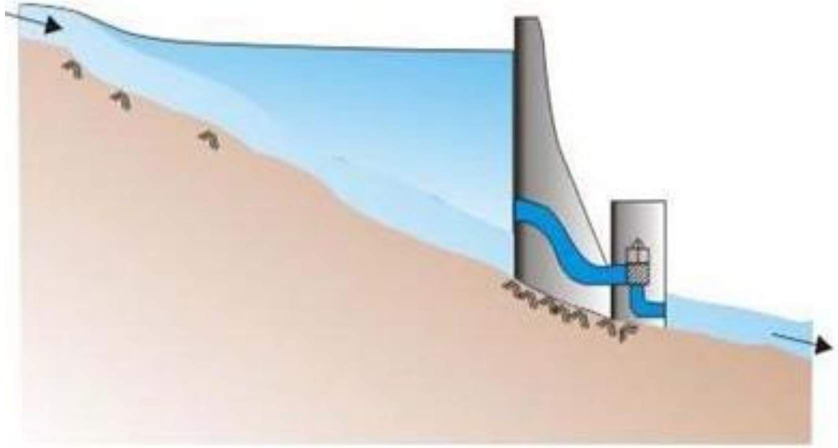
Source: http://www.laccei.org/LACCEI2010-Peru/Papers/Papers_pdf/ENE153_Jackson.pdf

Multipurpose:
When the water used in the hydropower plant is used for other purposes like irrigation, flood control etc.

Source: www.theconstructor.org

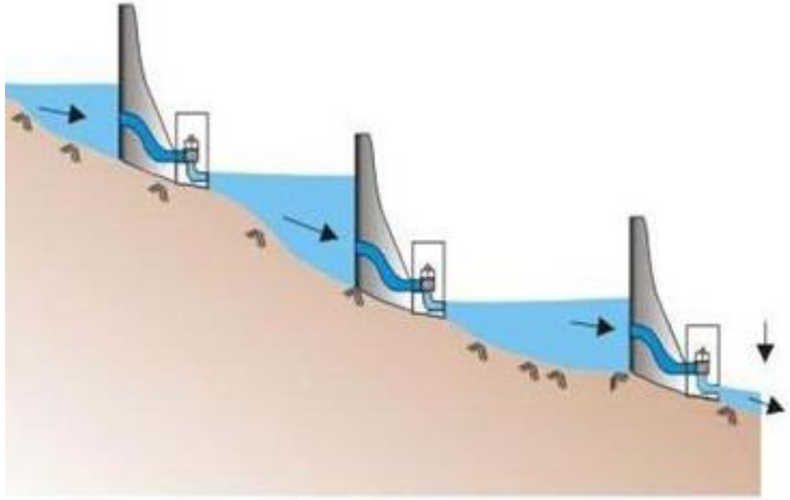
Classification according to hydrological relation

Single stage:
When the runoff from a single hydropower plant is diverted back into river.



(a)

Cascade system:
When two or more hydropower plants are used in series such that the runoff discharge of one is used as intake of the second plant.



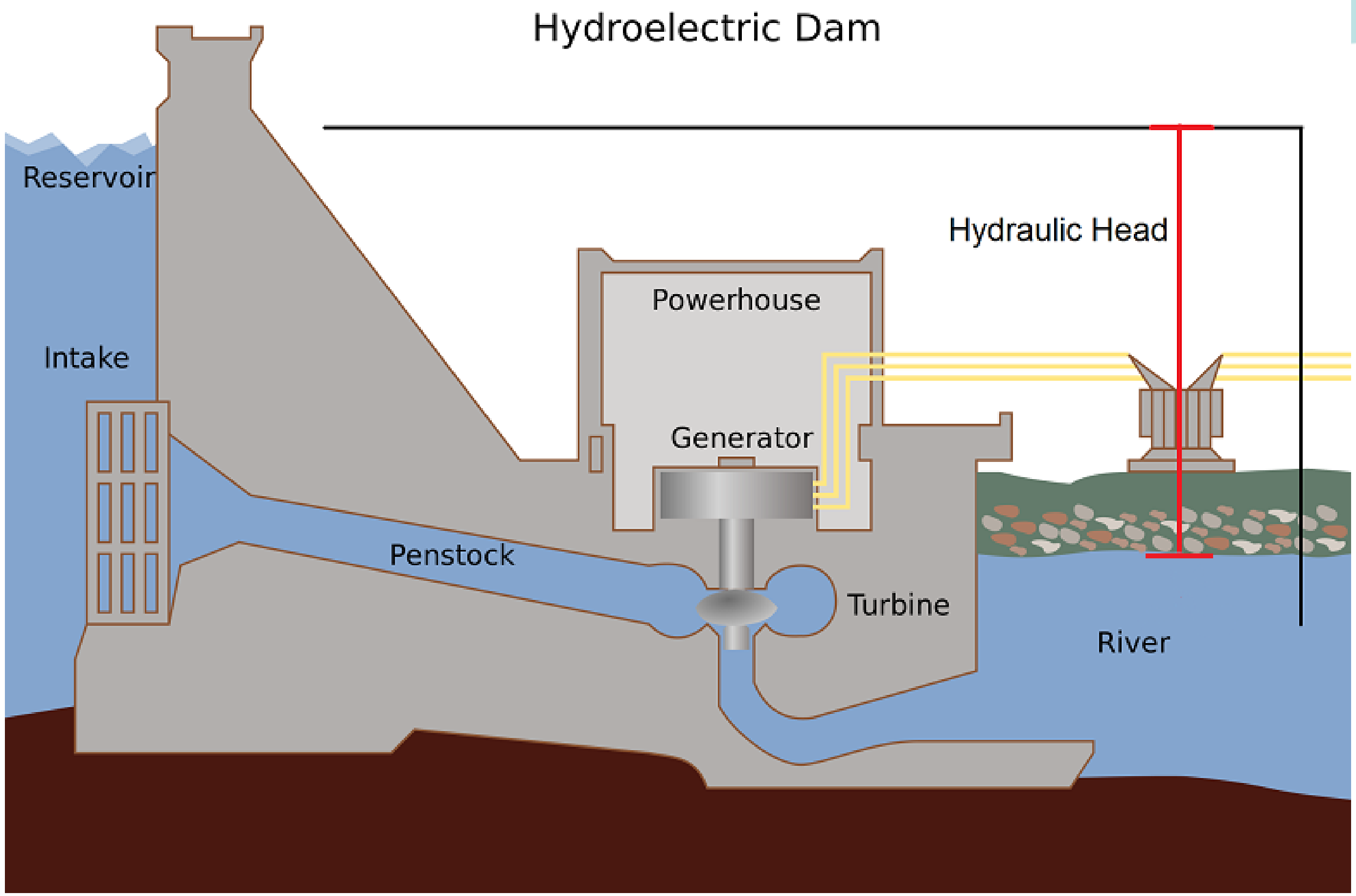
(b)

Source: https://slideplayr.com/slide/9289734/

Hydraulic head in hydropower

The **hydraulic head** is a value that measures the **amount of mechanical energy available** in water in a river, stream or even lake. It is a measurement of the height of a static water column above an arbitrary point, expressed in meters. The higher the water level or hydraulic head, the more energy that the water at a specific location has.

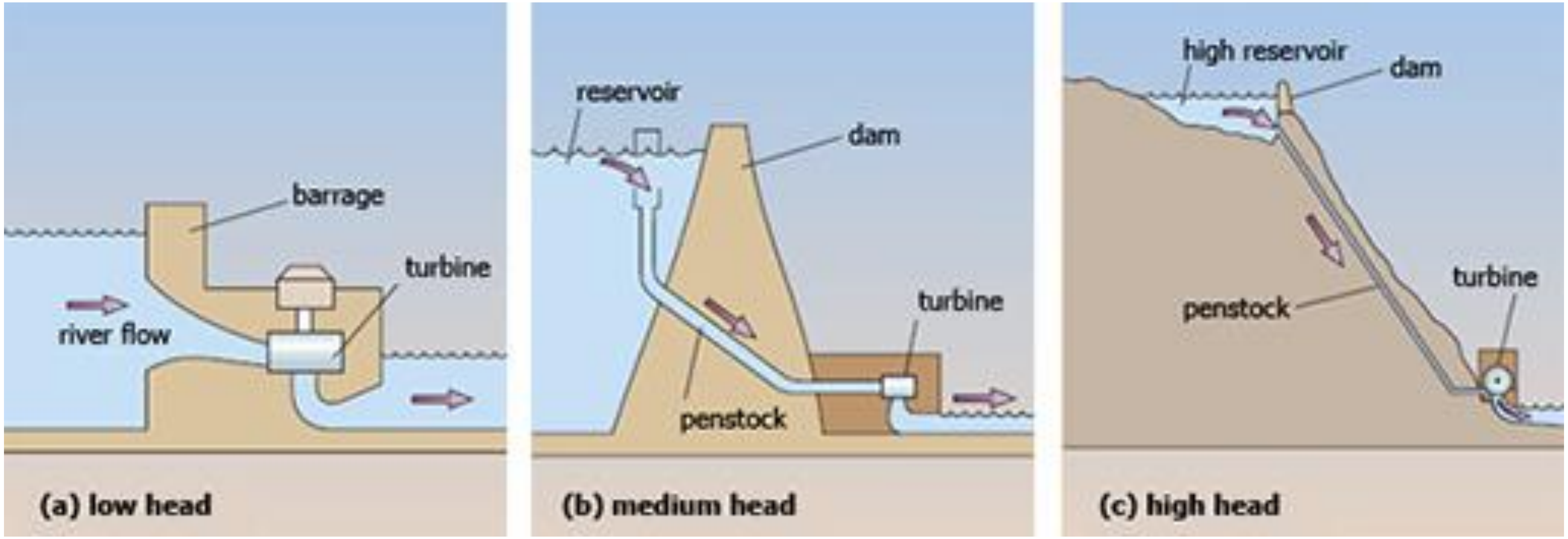
The energy used to generate electricity by moving the turbines arises from the utilisation of **gravitational potential energy** of the reservoir water as it moves down through the penstocks.



Source: https://energyeducation.ca/encyclopedia/Hydraulic_head

Hydraulic head in hydropower

Hydroelectric installations range in capacity from a few hundred watts to more than 10,000 megawatts (10 GW).



Source: https://www.open.edu/openlearn/mod/oucontent/view.php?id=73762&extra=thumbnailfigure_idm45249255027760

We can classify installations by:

- the effective head of water
- the capacity – the rated power output
- the type of turbine used
- the location and type of dam, reservoir, etc.

The available head is an important determinant of the other factors, and the head and capacity together largely determine the type of plant and installation.

Hydraulic head in hydropower

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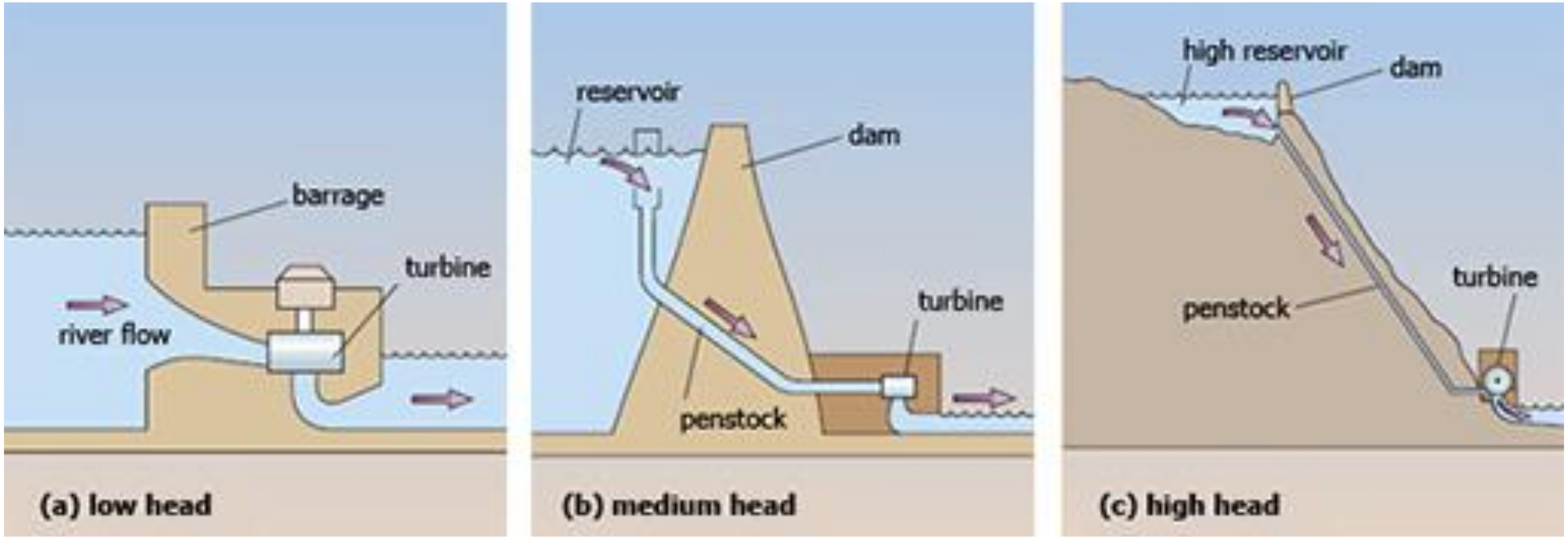

Source: https://www.open.edu/openlearn/mod/oucontent/view.php?id=73762&extra=thumbnailfigure_idm45249255027760

Low Head: Head differences of around 10 meters or less
Medium Head: Head differences between 10 and 100 meters.
High Head: Head differences of 100 meters or higher.

Stored energy of water

Water held at height represents stored energy – the gravitational (available) potential energy:

$$E = mgh$$

m = mass of water (kg)

g = Acceleration due to gravity (m/s^2)

h = Height of head (m)

Available power

Power is the rate of generation of energy, measured in watts (W) or joules per second (J/s)

The operational power, i.e. the rate of power generation, of the installation is calculated by: $P = n * \rho * g * Q * H_{net}$

Where:

P: the operational power (W)

n: the total efficiency of the turbine ($n = n_{tur} * n_{gen} * n_{trans}$) (approx. 0.8)

P: the density of water (1000 kg/m^3 at 4^{o}C)

g: the acceleration due to gravity (9.81m/s^2)

Q: the flow rate of the water (m^3/s)

H_{net}: the available hydraulic head (m) (height difference between inlet & outlet)

Available power calculation (example)

In a hydropower plant, **100**m^3/s of water flows from an elevation of **120**m to a turbine, where electric energy is generated. The total head loss in the piping system between points 1 & 2 (excluding the turbine unit) is 35m. If the efficiency of the turbine-generator is **80%**, calculate the electric power output.

$$P = n * \rho * g * Q * H_{net}$$

Where:

P: the operational power (W)

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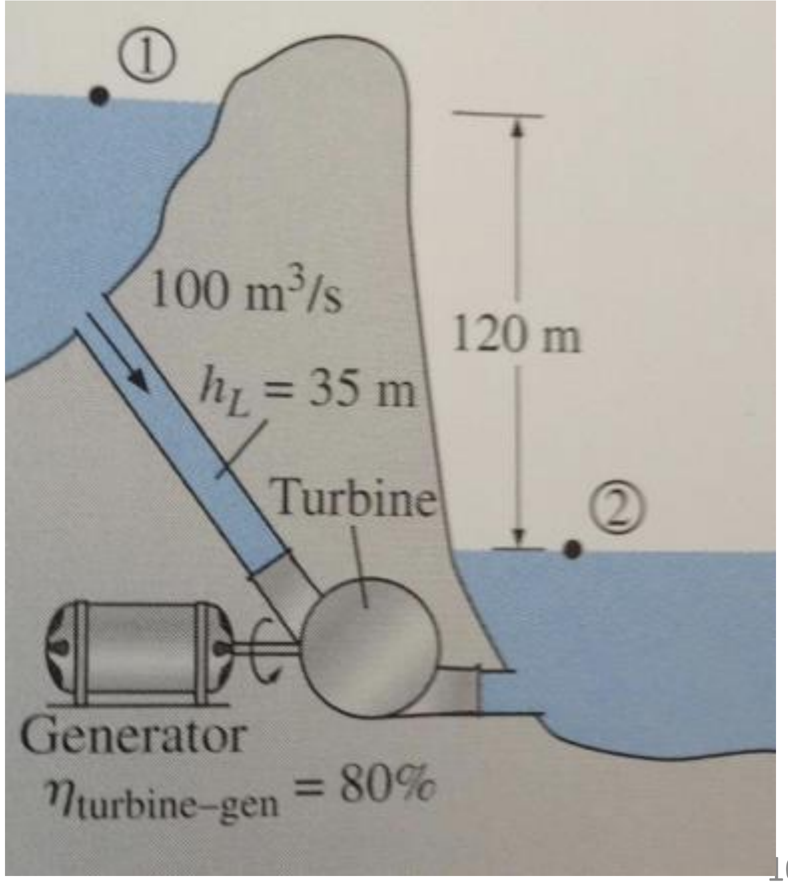
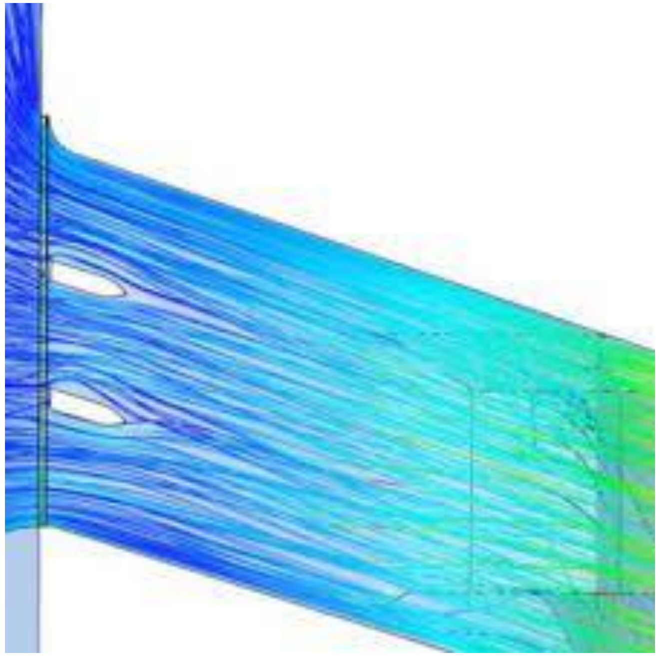


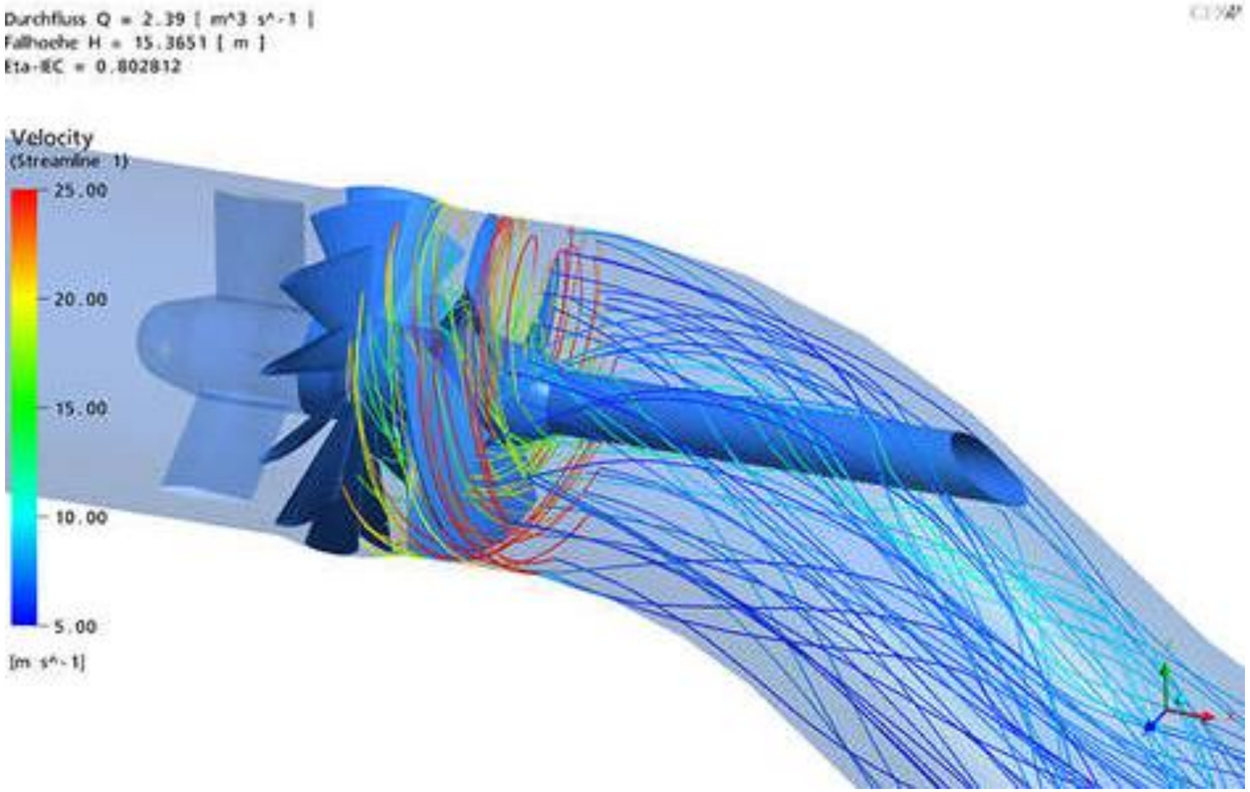
$$P = 0.8 * 1000 * 9.81 * 100 * 120$$

=94.176 KW

Available power

CFD simulation for the hydropower plant's efficiency





Source: http://www.hfm.tugraz.at/en/references/turbine/cfd-calculations-for-a-hydro-power-plant.html

Capacity factor

The **capacity factor** of a hydroelectric power plant is the amount of electricity that it produces over a period of time, divided by the amount of electricity it could have produced if it had run at full power over that time period.

Example

A hydro power plant of capacity 12 MW generates 30 million kWh of electricity in a year. What is its capacity factor?

capacity factor = annual output / maximum possible annual output

(Hours in one year = 8760)

1 MW plant running continuously at its rated capacity would generate = 8760 MWh/year

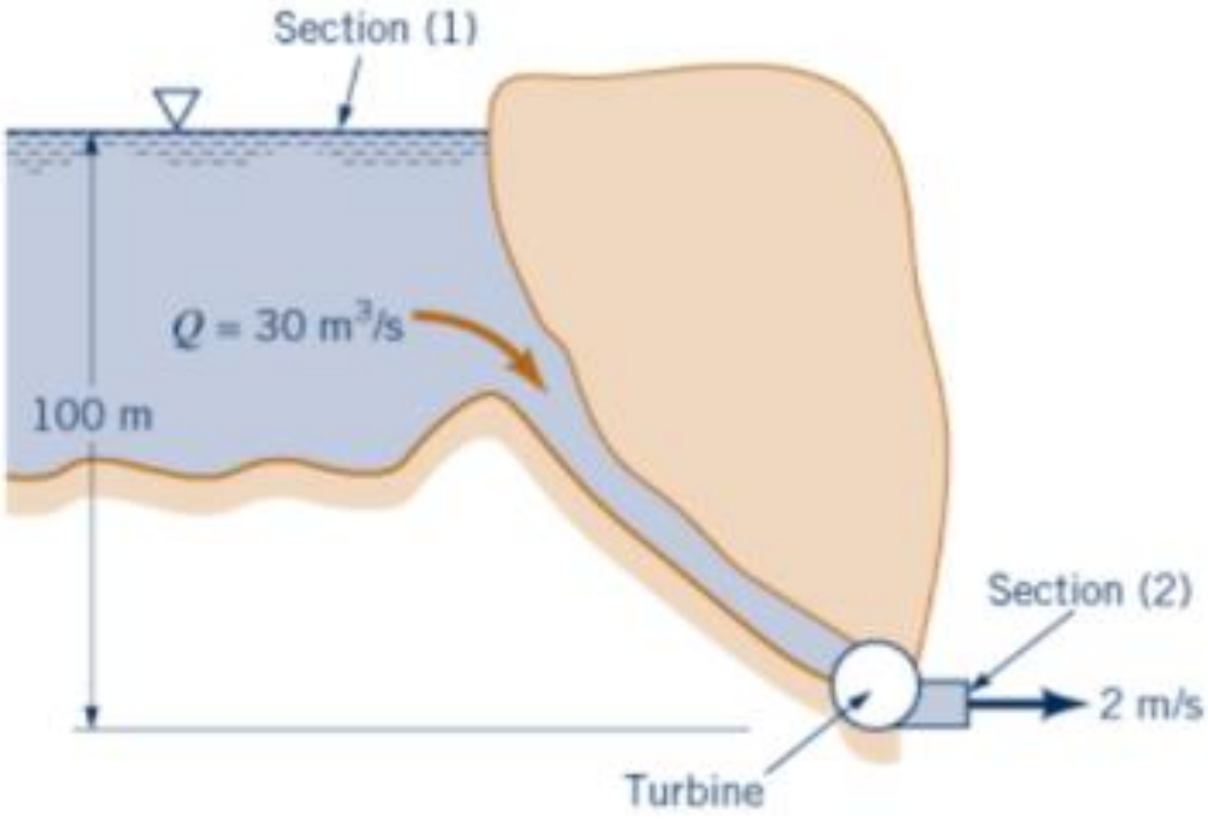
Capacity factor = (30 x 1000000 x 1000) / (12000000 x 8760) = 0.285 = 28.5%

Head losses in hydropower plants

Energy losses occur whenever water flows through pipes due to friction and this reduces the actual rate of power production.
These losses reduce the overall head and result in a number known as the effective head or net head.

Effective head is equal to the gross head minus the sum of all head losses. Head losses occur in all hydroelectric facilities, and are classified as major and minor head losses.

These hydraulic head losses are measured, calculated, and expressed in the same way hydraulic head is, in the equivalent height of water in meters. In this case, you subtract the amount of power lost through head losses from the overall gross power to get the actual net power one can obtain.

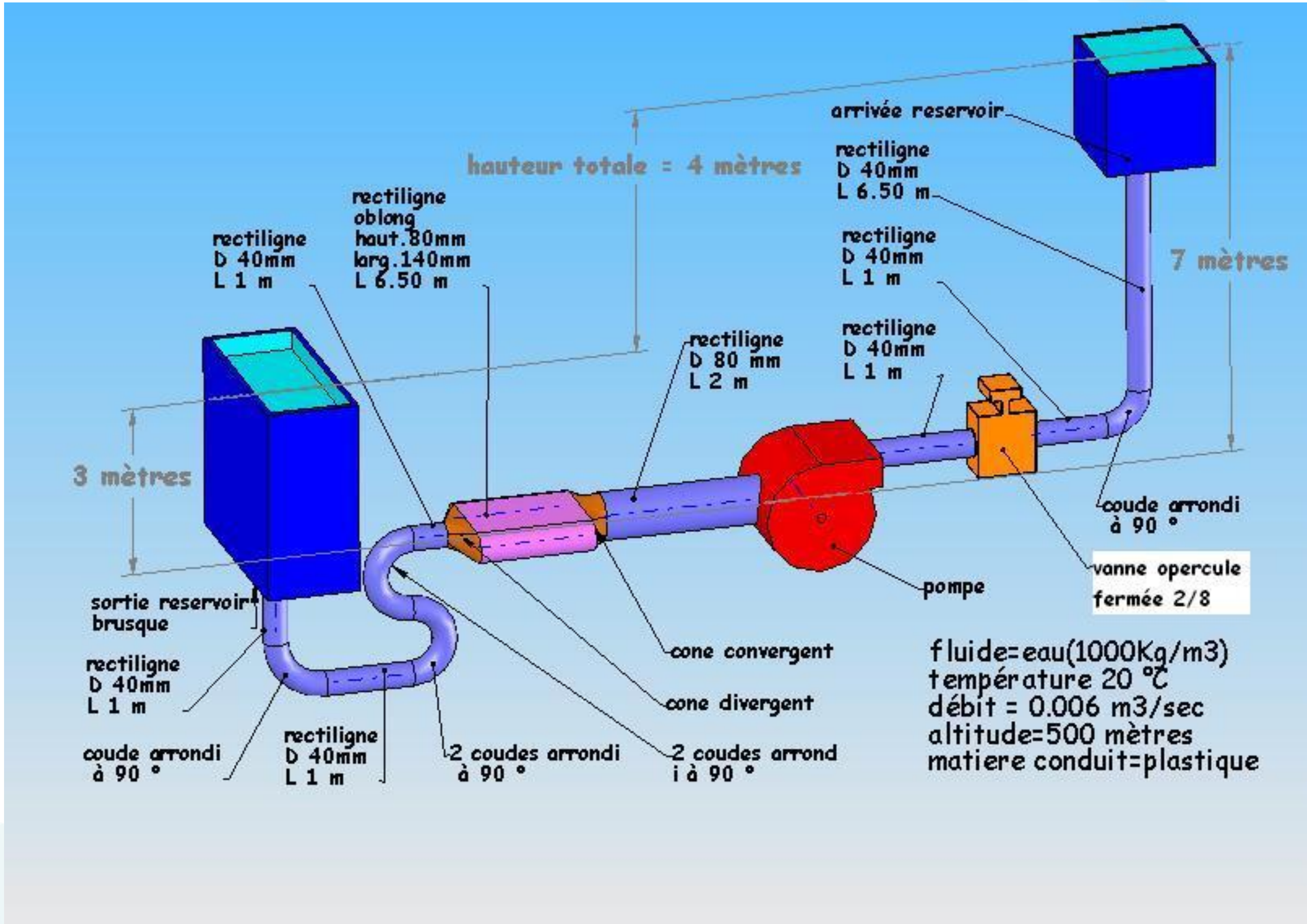


Head losses in hydropower plants

Types of head losses include:

Major head losses: Mainly from friction in the pipes, and occur over long lengths of pipe, such as in the penstock.

Minor head losses: From any other place besides friction in the pipes. Essentially, any place that the pipe bends or the velocity of the water changes, minor losses exist.



Source: https://www.mecaflux.com/en/mecanique_fluides_flux_internes.htm

Calculation of the head loss in a pipeline (Darcy's equation)

$$h_f = f \cdot \frac{L}{D} \cdot \frac{c^2}{2 \cdot g}$$

Head loss is **potential energy that is converted to kinetic energy**. Head losses are due to the frictional resistance of the piping system (pipe, valves, fittings, entrance, and exit losses).

Where:

h_f	=	Head loss	[m]
f	=	Friction factor	[-]
L	=	Length of pipe	[m]
D	=	Diameter of the pipe	[m]
c	=	Water velocity	[m/s]
g	=	Gravity	[m/s^2]

The Darcy–Weisbach equation is an empirical equation that relates the head loss, or pressure loss, due to friction along a given length of pipe to the average velocity of the fluid flow for an incompressible fluid.

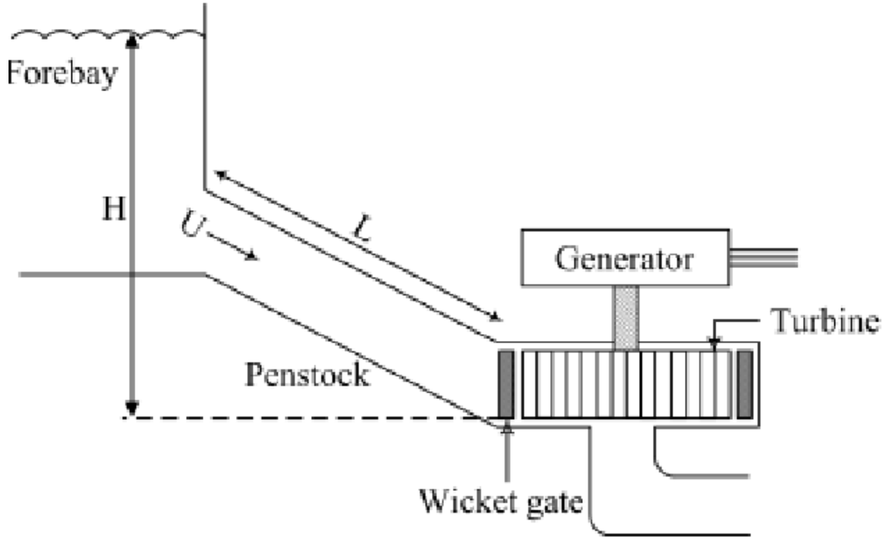
Calculation of the head loss in a pipeline (example)

Power Plant data:

H	=	100 m	Head
Q	=	10 m^3/s	Flow Rate
L	=	1000 m	Length of pipe
D	=	2,0 m	Diameter of the pipe

The pipe material is steel

$$h_f = f \cdot \frac{L}{D} \cdot \frac{c^2}{2 \cdot g}$$



Source: https://www.semanticscholar.org/paper/Review-of-Hydropower-Plant-Models-Acakpovi-Hagan/ea501a0e48c1ad1ceb2f7f568b554287b6df086e/figure/0

The dimensionless Reynolds number (Re), is used to determine whether the fluid flow is laminar or turbulent.

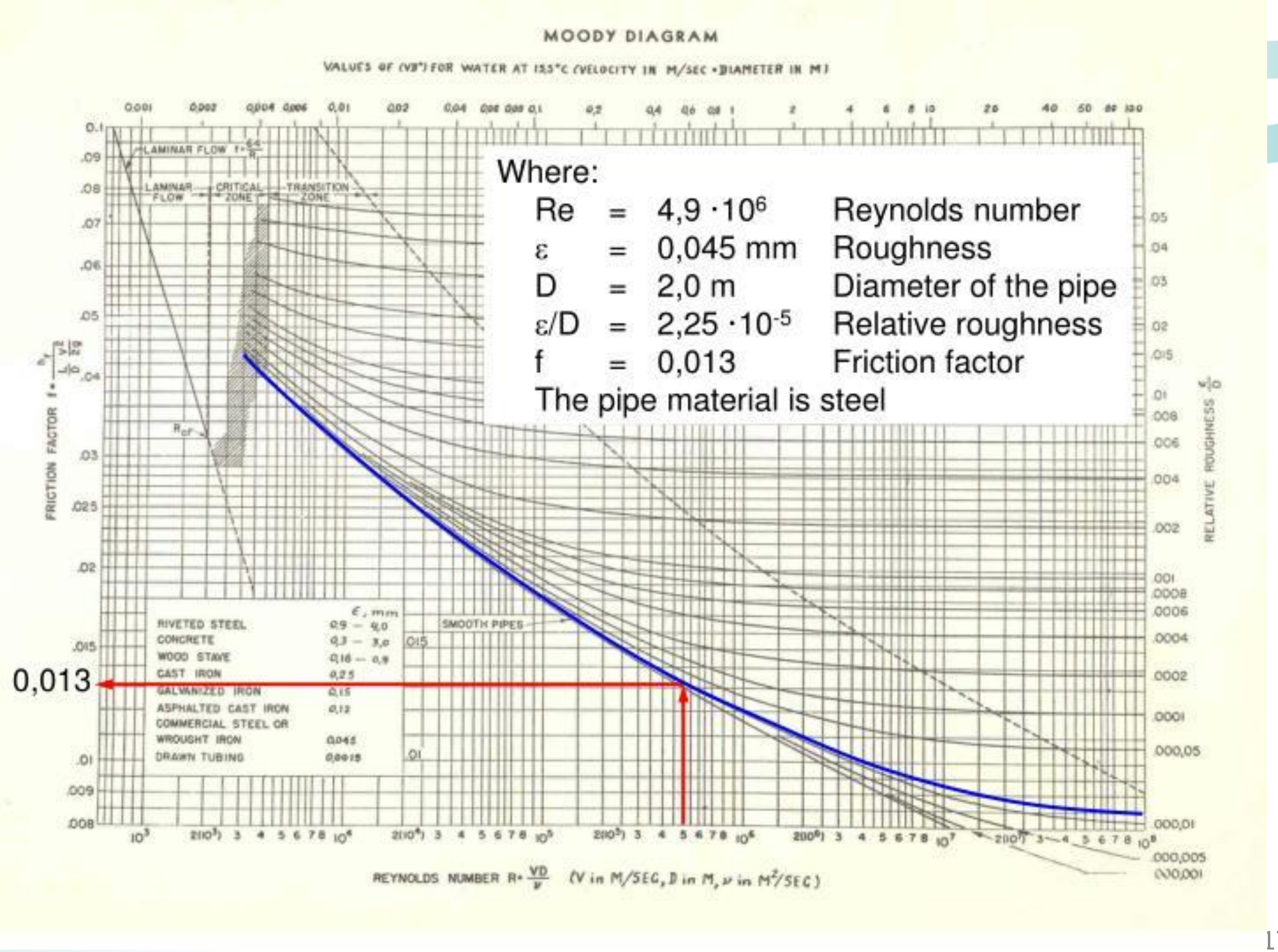
$$Re = \frac{c \cdot D}{\upsilon}$$

Where:

c	=	3,2 m/s	Water velocity
ν	=	$1{,}308 \cdot 10^{-6}$ m^2/s	Kinetic viscosity
Re	=	$4{,}9 \cdot 10^6$	Reynolds number

Calculation of the head loss in a pipeline (example)

The Moody diagram is a non-dimensional graph that relates the Darcy's friction factor f, Reynolds number Re, and surface roughness for fully developed flow in a circular pipe. It can be used to predict pressure drop or flow rate down such a pipe.



Calculation of the head loss in a pipeline (example)

Power Plant data:

H	=	100 m	Head
Q	=	10 m^3/s	Flow Rate
L	=	1000 m	Length of pipe
D	=	2,0 m	Diameter of the pipe

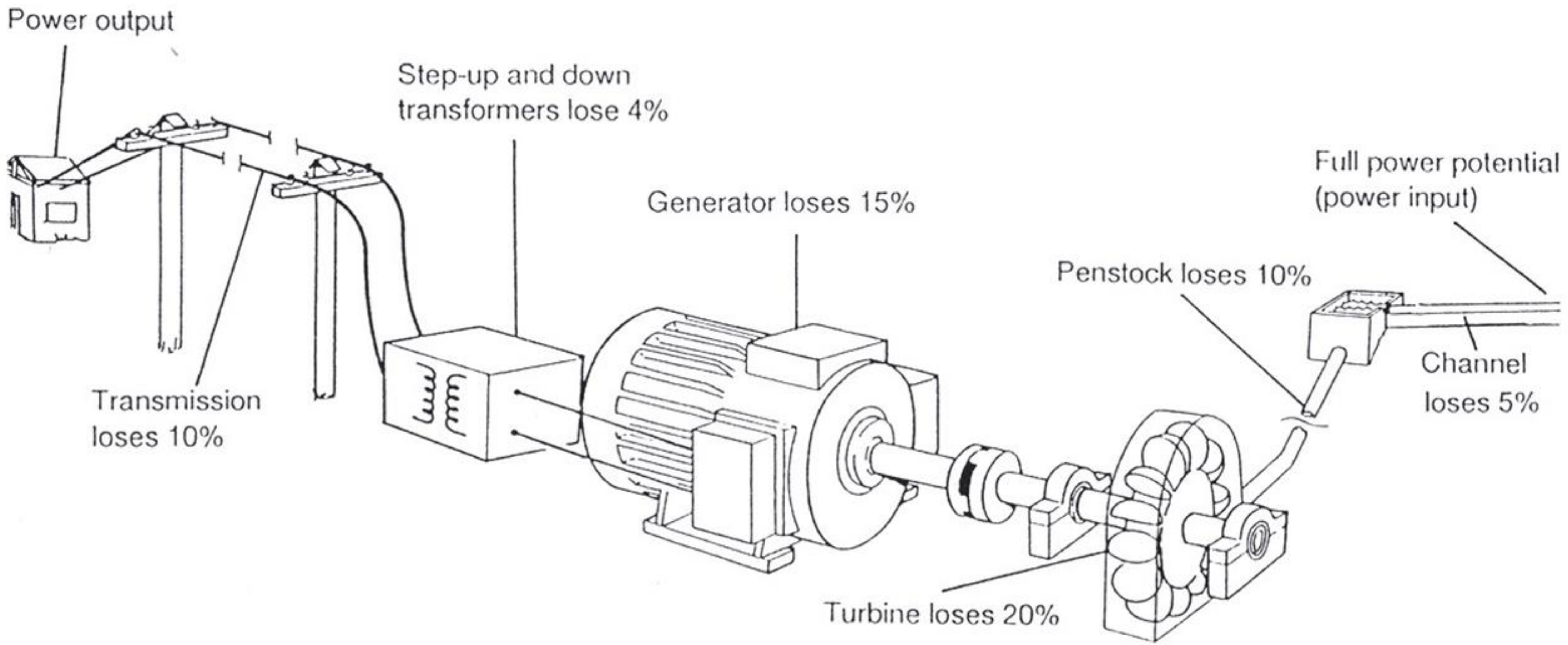
The pipe material is steel

$$h_f = f \cdot \frac{L}{D} \cdot \frac{c^2}{2 \cdot g} = 0{,}013 \cdot \frac{1000}{2} \cdot \frac{3{,}2^2}{2 \cdot 9{,}82} = 3{,}4 \text{ m}$$

Where:

f	=	0,013	Friction factor
c	=	3,2 m/s	Water velocity
g	=	9,82 m/s^2	Gravity

Other losses in hydropower plants

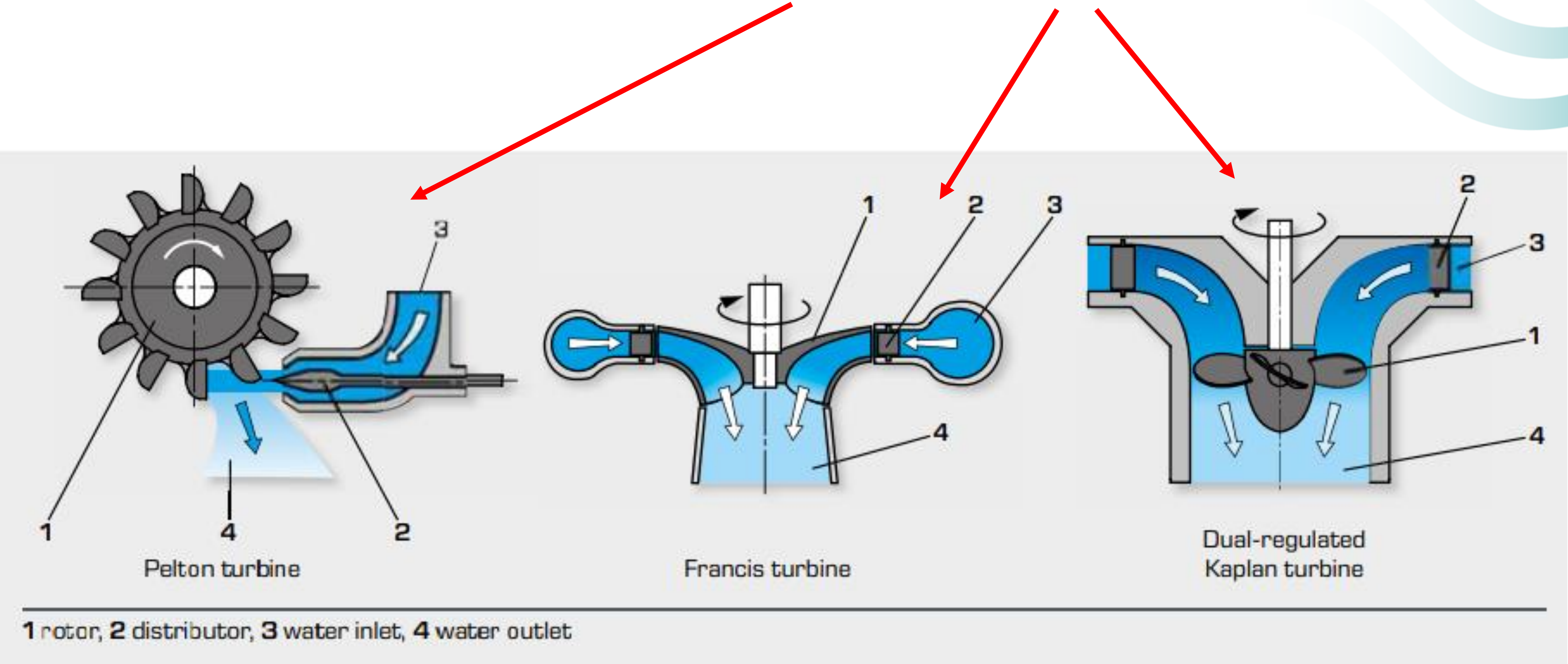


Overall losses are about 50%

Turbines

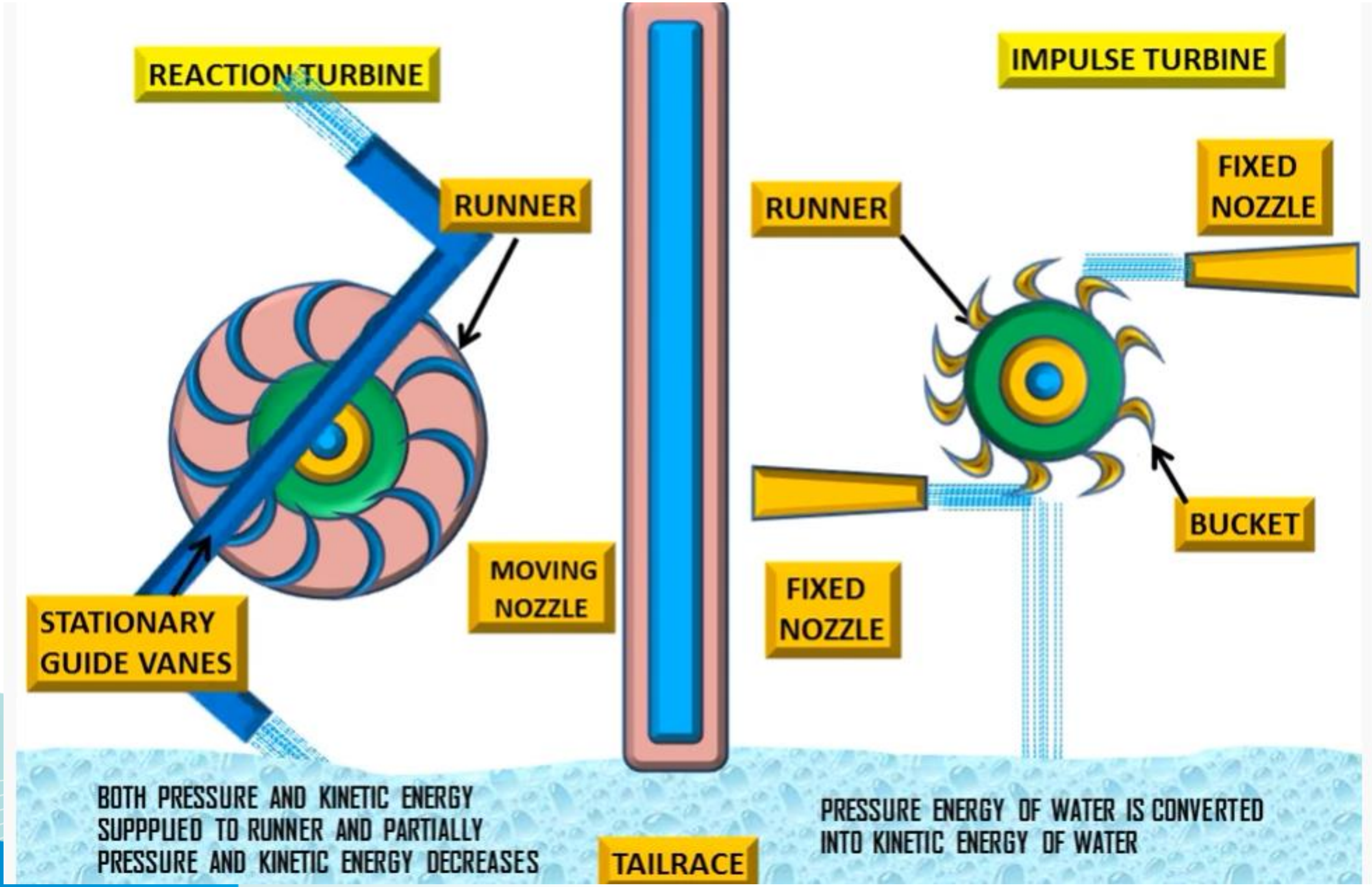
- Many types of turbines have been developed over the centuries.
- The water wheel is the ancestor of the modern turbine.
- Hydro-turbines are engines through which the energy of liquid is converted into mechanical energy.
- Turbines can be classified according to the height of heads.
- Turbines are also classified according to their principle way of operating and can be either impulse or reaction turbines.

Classification of turbines: Impulse and Reaction Turbines



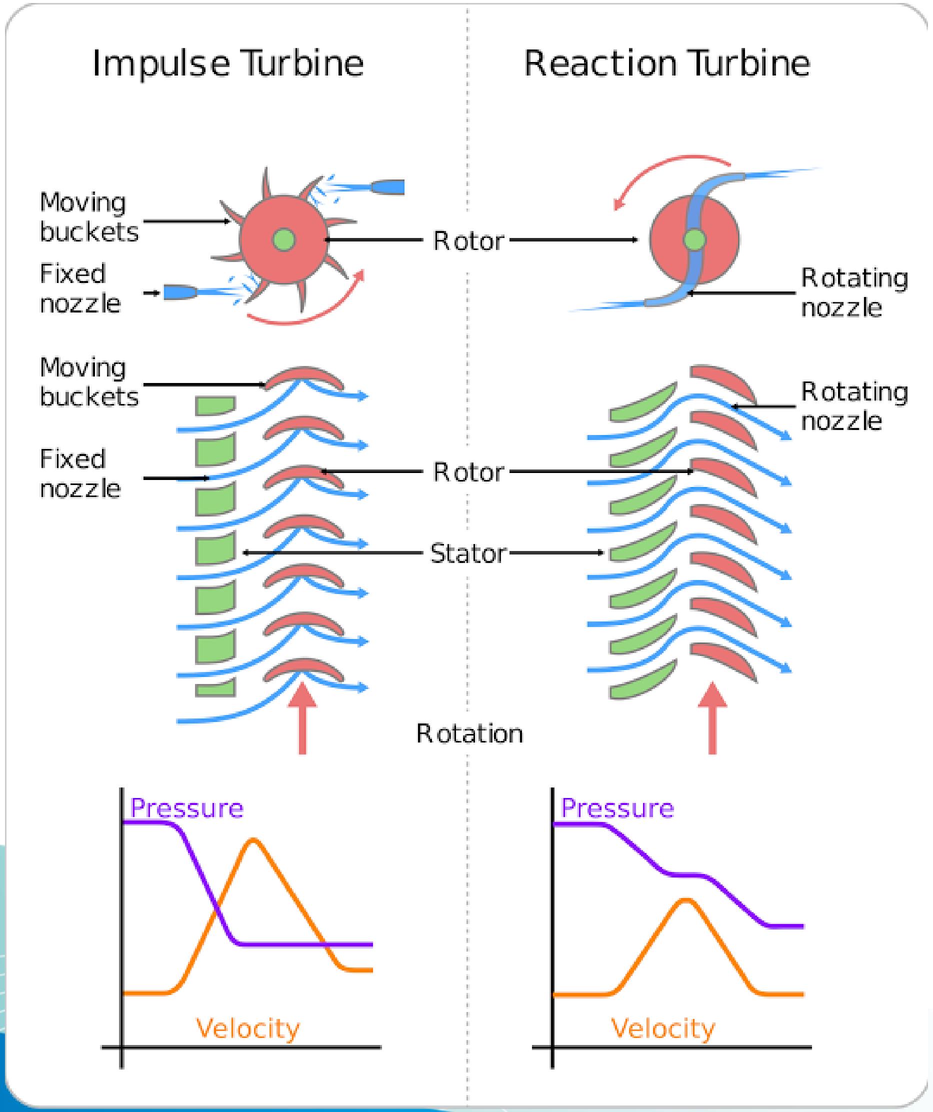
Source: https://www.youtube.com/watch?v=3AD_Hiy2QjM

Classification of turbines: Impulse and Reaction Turbines



Source: https://www.youtube.com/watch?v=3AD_Hiy2QjM

Difference between Impulse and Reaction Turbine



Impulse Turbine	Reaction Turbine
1. In impulse turbine only kinetic energy is used to rotate the turbine.	1. In reaction turbine both kinetic and pressure energy is used to rotate the turbine.
2. In this turbine water flow through the nozzle and strike the blades of turbine.	2. In this turbine water is guided by the guide blades to flow over the turbine.
3. All pressure energy of water converted into kinetic energy before striking the vanes.	3. In reaction turbine, there is no change in pressure energy of water before striking.
4. The pressure of the water remains unchanged and is equal to atmospheric pressure during process.	4. The pressure of water is reducing after passing through vanes.
5. Water may admitted over a part of circumference or over the whole circumference of the wheel of turbine.	5. Water may admitted over a part of circumference or over the whole circumference of the wheel of turbine.
6. In impulse turbine casing has no hydraulic function to perform because the jet is at atmospheric pressure. This casing serves only to prevent splashing of water.	6. Casing is absolutely necessary because the pressure at inlet of the turbine is much higher than the pressure at outlet. It is sealed from atmospheric pressure.
7. This turbine is most suitable for large head and lower flow rate. Pelton wheel is the example of this turbine.	7. This turbine is best suited for higher flow rate and lower head situation.

Difference between Impulse and Reaction Turbine

Reaction turbines

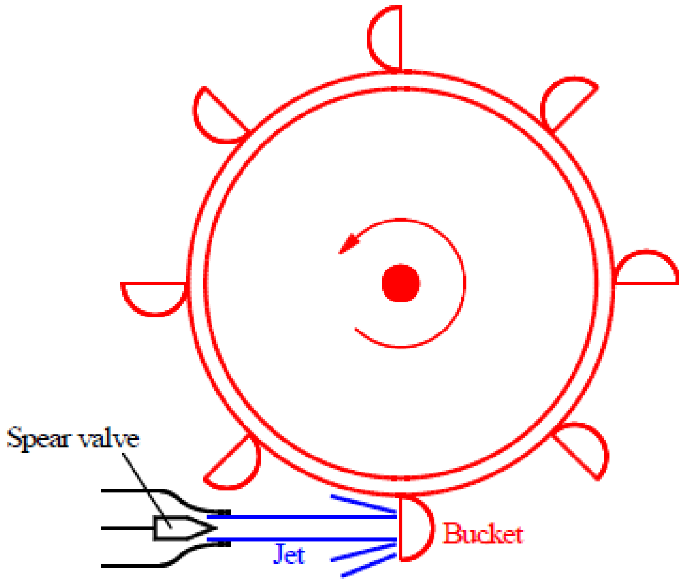
- Both pressure and velocity changes as the water passes through the turbine runner.
- Pressure drop across the turbines is the main source of energy to turn the turbine.
- Turbine blades are always completely immersed in water.
- Water enters and leaves the turbine axially.
- Well suited to low and medium head applications.
- Examples are **Propeller turbines** and **Kaplan turbines** and **Francis turbines**.

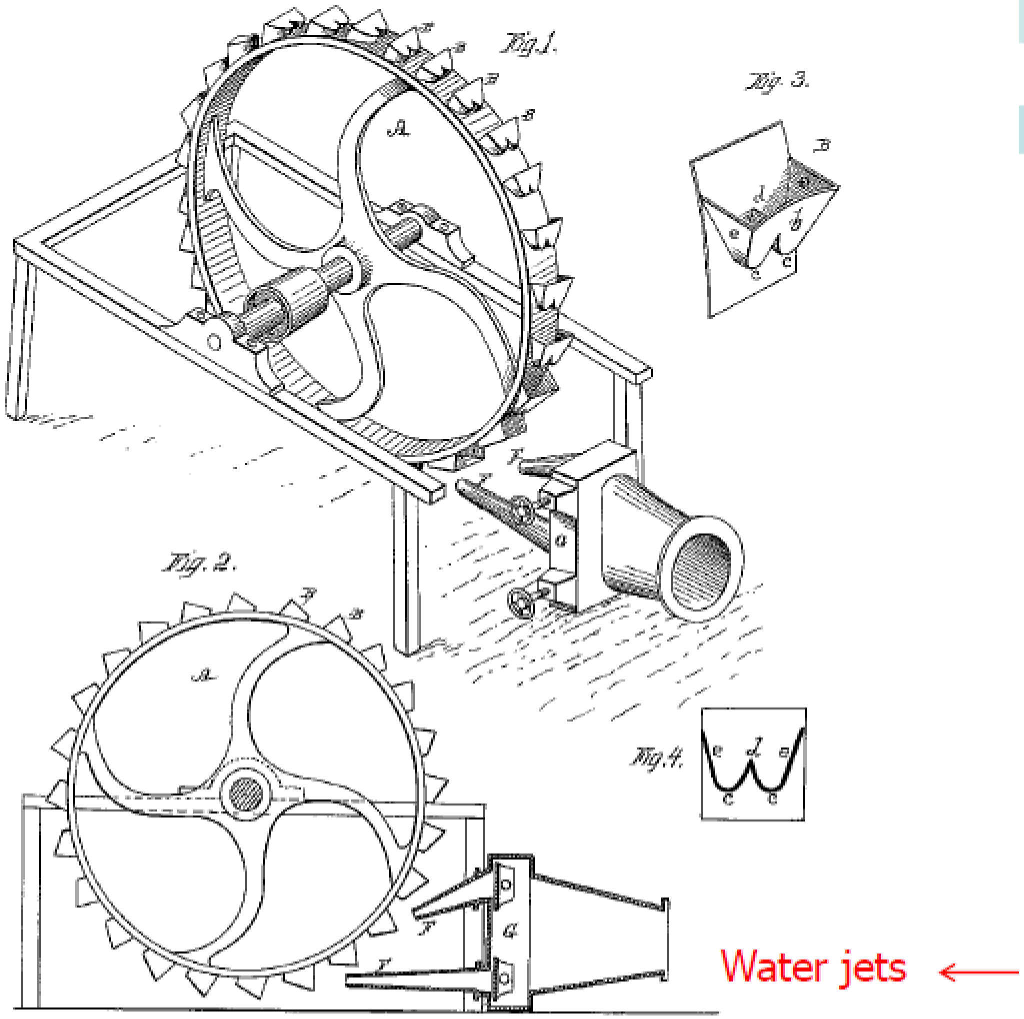
Impulse turbines

- The velocity of water jet changes but the pressure throughout remains atmospheric
- Kinetic energy in the water jet is the main source of energy to turn the turbine.
- Turbine is not immersed in water.
- Water jet hits the turbine tangentially.
- Well suited to high head applications.
- Examples are **Pelton wheel, Cross-flow** and **Turgo** turbines

Water turbines (Impulse)

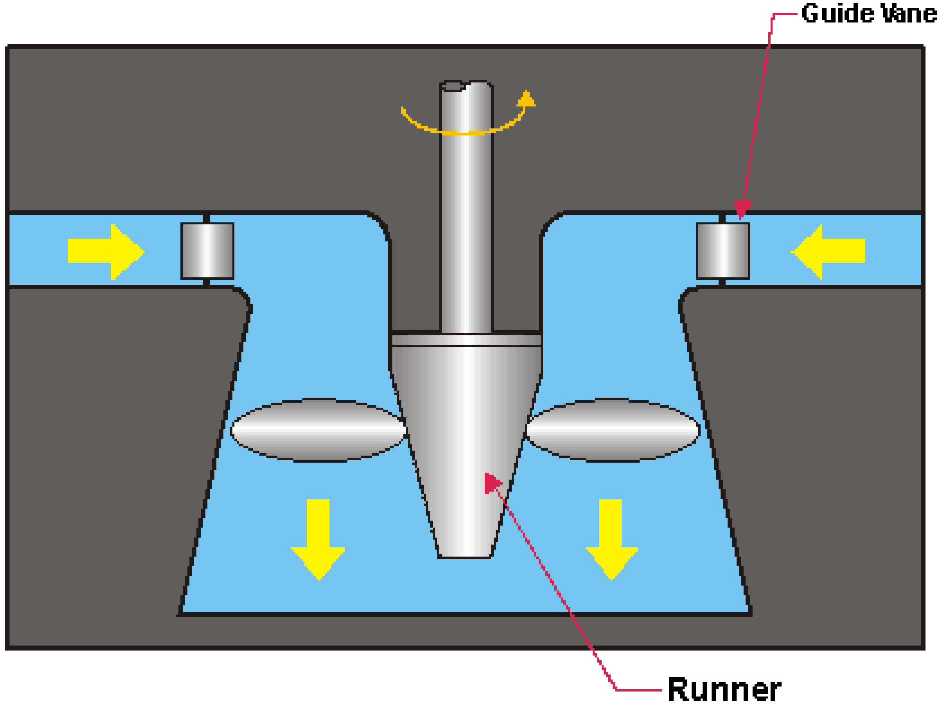
- Nozzles fire water jets onto vanes attached to the periphery of a rotating wheel.
- Rate of change of angular momentum and motion of vanes causes work to be done on the runner (impeller), so transferring energy.
- Fluid energy is entirely kinetic so absolute velocity at outlet is smaller than at inlet (jet velocity).
- Fluid pressure is atmospheric throughout and the relative velocity is constant except for a small loss due to friction.





Kaplan turbine (Reaction) – Low Head

- The Kaplan turbine is a propeller type reaction turbine.
- Water enters and leaves the turbine axially.
- Kaplan turbine efficiencies are typically over 90%, but may be lower in very low head applications.
- Kaplan turbines are widely used throughout the world for electrical power production.
- They cover the lowest head hydro sites (1.5m to 20m) and are especially suited for high flow conditions.



Francis turbine (Reaction) – Medium Head

- The Francis turbine is a reaction turbine, which means that the working fluid changes pressure as it moves through the turbine, giving up its energy.

- The inlet is spiral shaped. Guide vanes direct the water tangentially to the runner. This radial flow acts on the runner vanes, causing the runner to spin.

- Guide vanes control both the direction and quantity of water flowing onto the turbine runner.

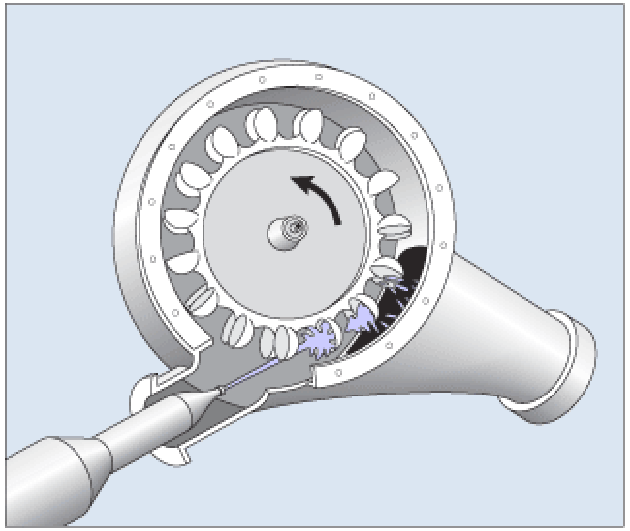
- Francis turbines are the most common water turbine in use today.

- They operate in a head range of ten meters to several hundred meters.

- They can also be used in reverse as pumps.

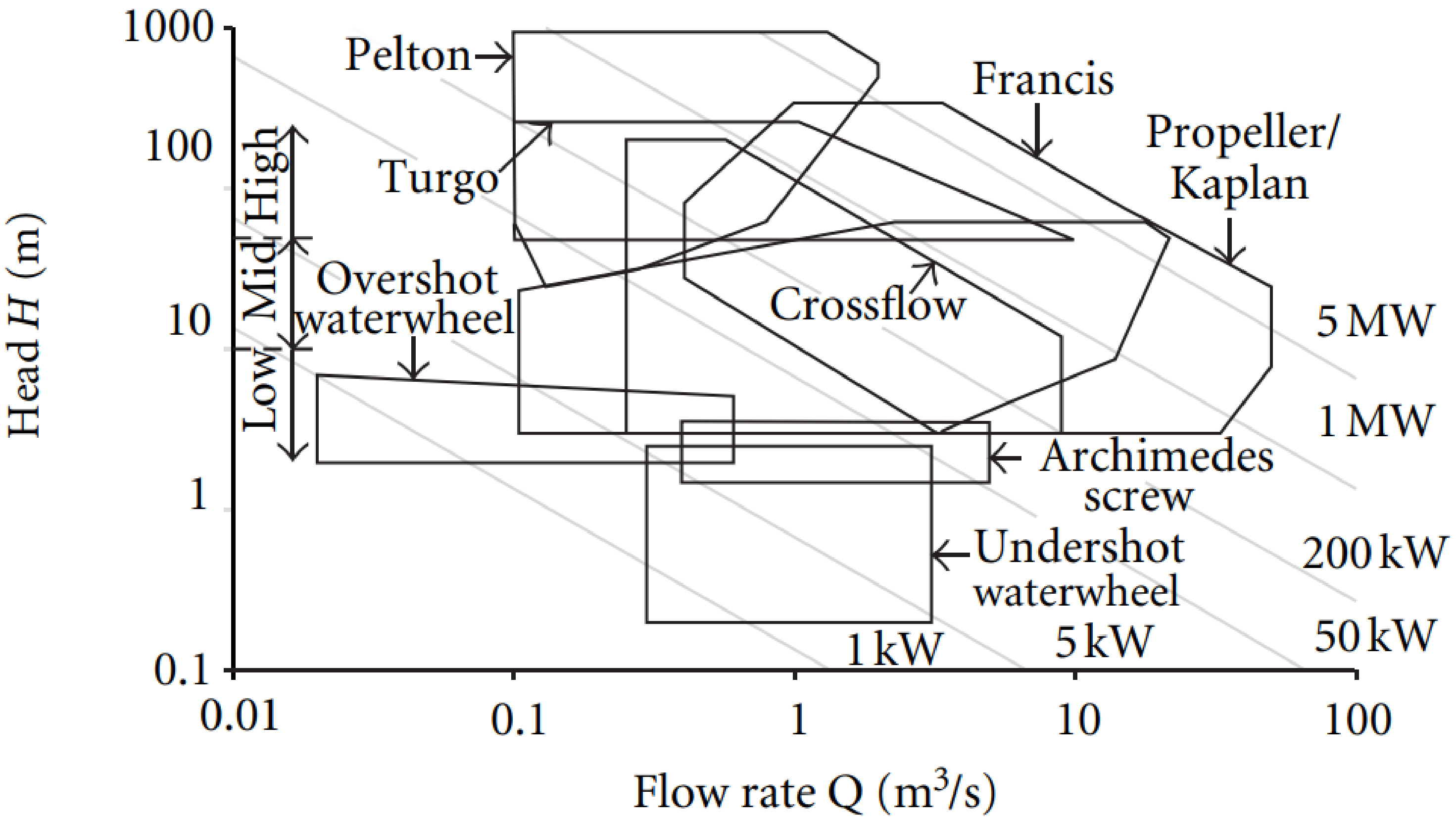
Pelton wheel turbine (Impulse) – High Head

- It is a tangential flow impulse turbine.
- Nozzles direct forceful streams of water against a series of spoon-shaped buckets mounted around the edge of a wheel.
- Each bucket reverses the flow of water, leaving it with diminished energy. The resulting impulse spins the turbine.
- The buckets are mounted in pairs, to keep the forces on the wheel balanced, as well as to ensure smooth, efficient momentum transfer of the fluid jet to the wheel.
- The Pelton wheel is most efficient in high head applications.
- They can operate with heads as high as 1,800 meters.



Turbine applications

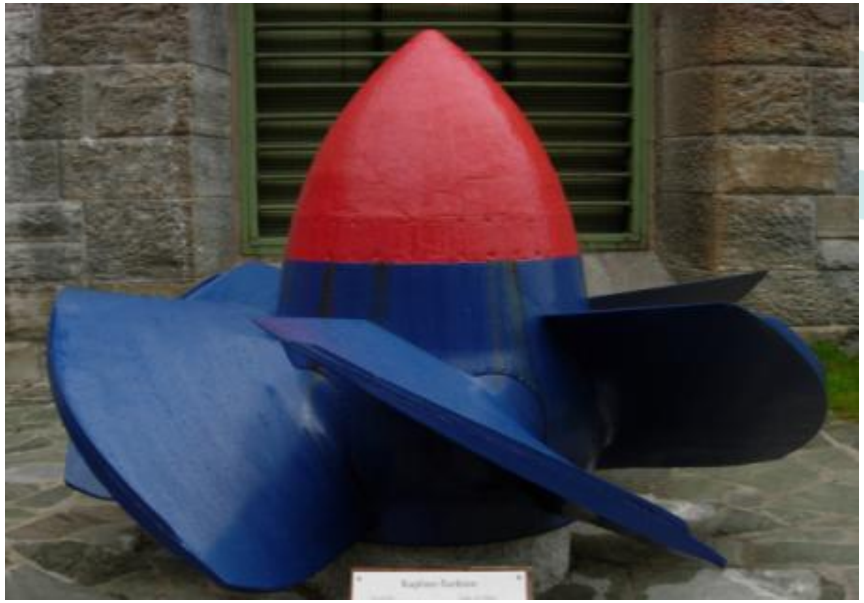
Different turbines are used for different applications. The choice of turbine depends upon how much head and flow are available.

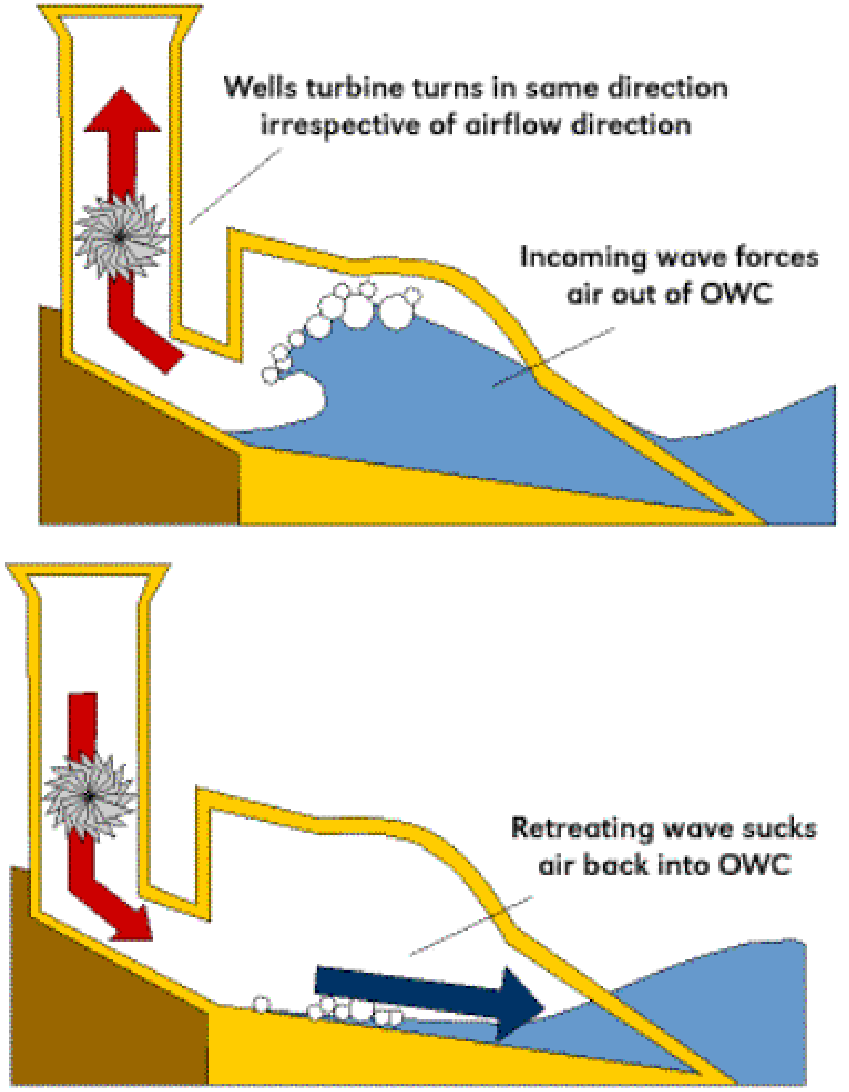


Source: https://www.researchgate.net/publication/258403445_Potential_of_Small-Scale_Hydropower_for_Electricity_Generation_in_Sub-Saharan_Africa/figures?lo=1&utm_source=google&utm_medium=organic

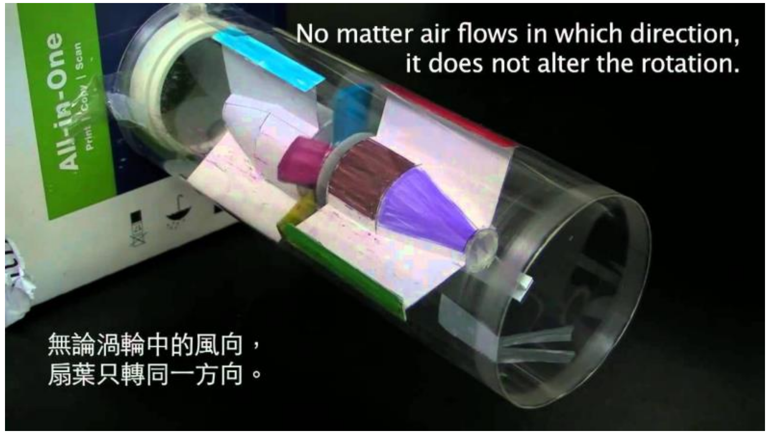
Water turbines - Common Types

Kaplan turbines are axial-flow (propeller) turbines. In the Kaplan design the blade angles are adjustable to ensure efficient operation for a range of discharges.



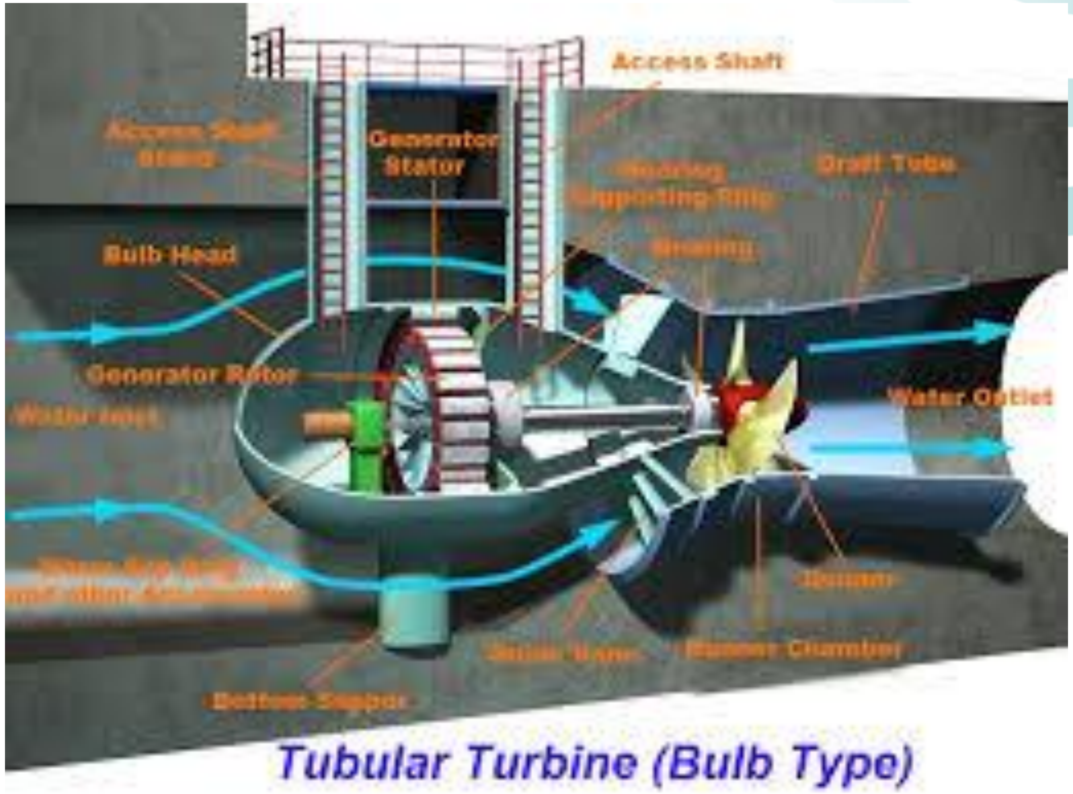


Wells turbines were specifically developed for wave-energy applications. They have the property that they rotate in the same direction irrespective of the flow direction.



Water turbines - Common Types

Bulb generators are large-diameter variants of the Kaplan propeller turbine, which are suitable for the low-head, high-discharge applications in tidal barrages (e.g. La Rance in France). Flow passes around the bulb, which contains the alternator.

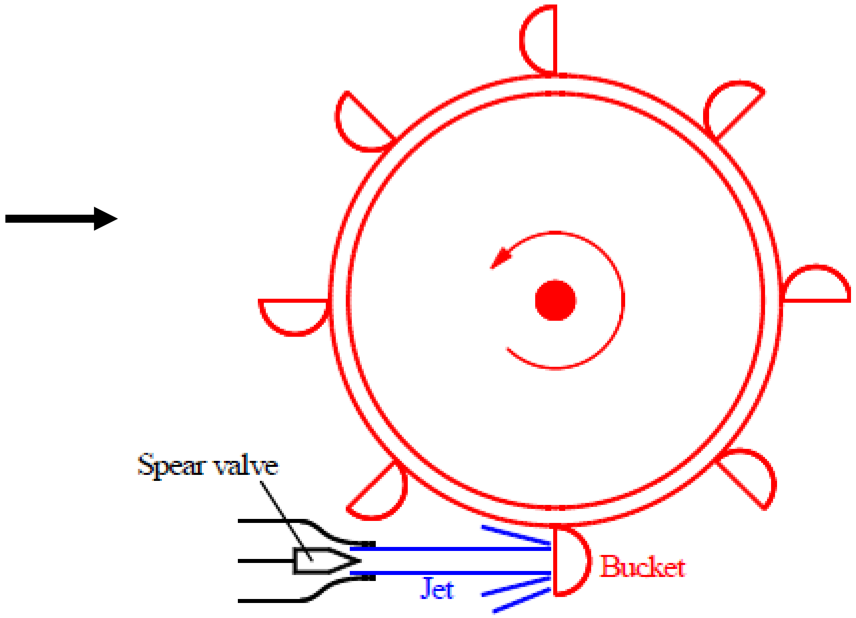


Tubular Turbine (Bulb Type)

The ***Archimedes screw*** has been used since ancient times to raise water. It is widely used in water treatment plants because it can accommodate submerged debris. Recently, several devices have been installed beside weirs in the north of England to run in reverse and generate power.

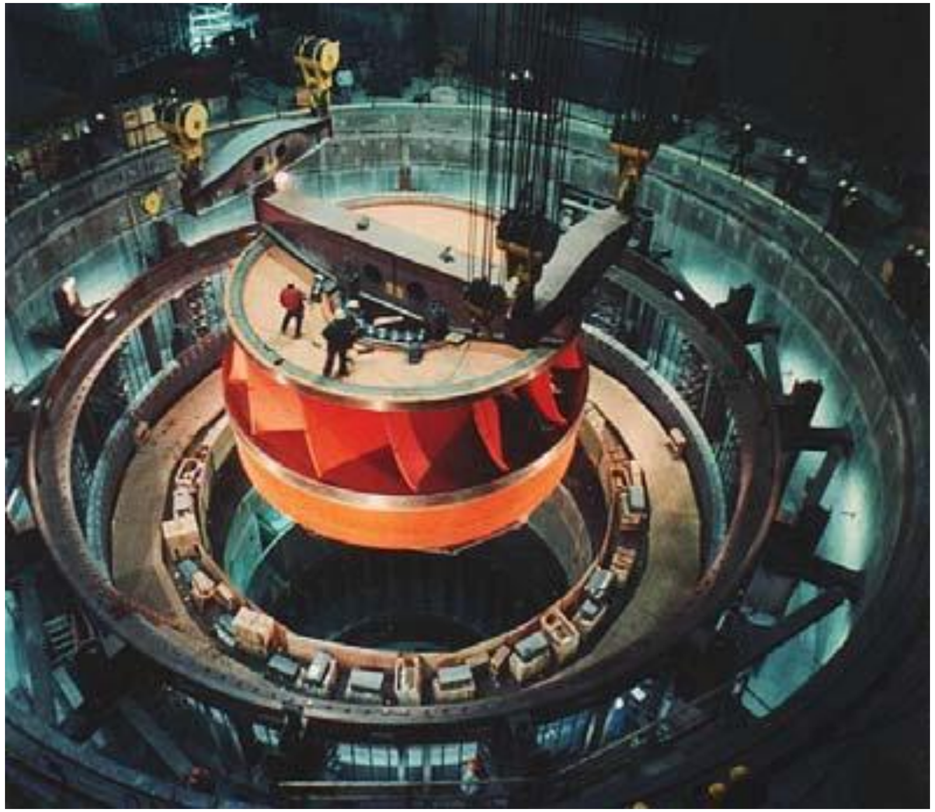
Water turbines - Common Types

Pelton wheels are impulse turbines used in hydroelectric plant where there is a very high head of water. Typically, 1 – 6 high-velocity jets of water impinge on buckets mounted around the circumference of a runner.



Francis turbines are used in many large hydropower projects (e.g the Hoover Dam), with an efficiency in excess of 90%. Such moderate- to high-head turbines are also used in *pumped-storage* power stations which pump water uphill during periods of low energy demand and then run the system in reverse to generate power during the day. This smooths the power demands on fossil-fuelled and nuclear power stations which are not easily brought in and out of operation. Francis turbines are like centrifugal pumps in reverse.

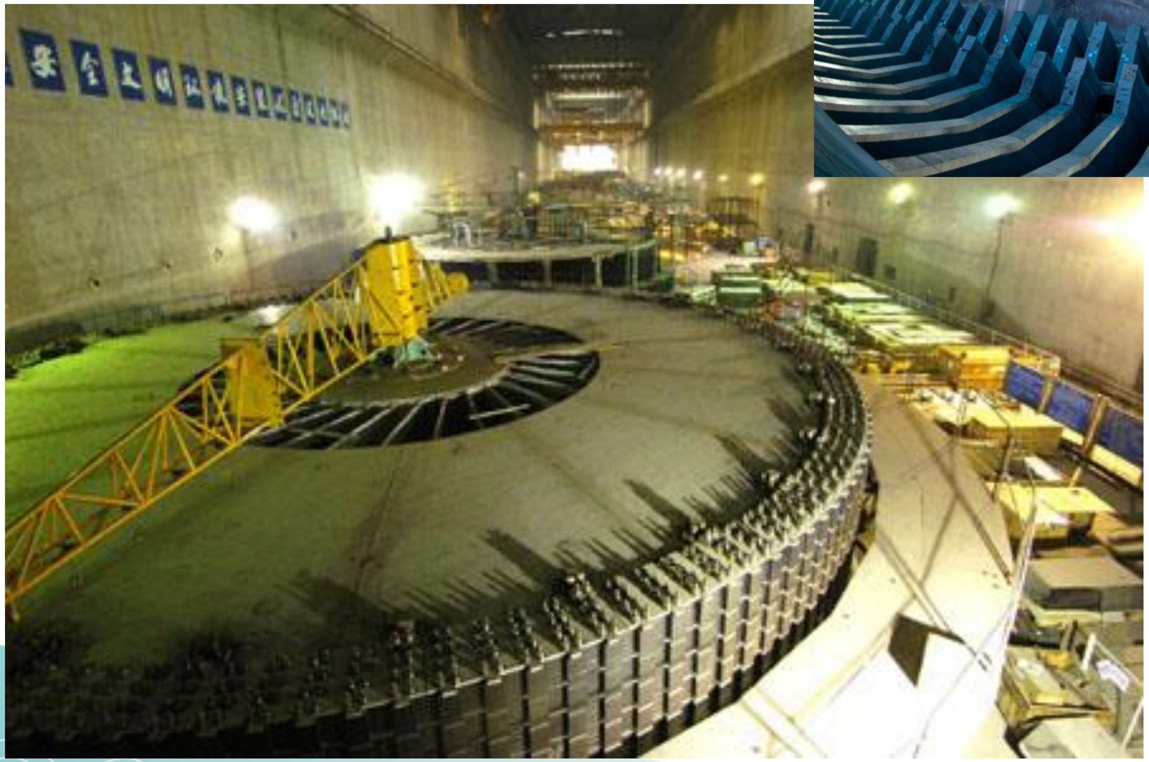
Hydropower plants - turbines



75 MW Francis turbine,
Grand Coulee Dam, USA

14 MW. Xiluodu Hydropower Station, China

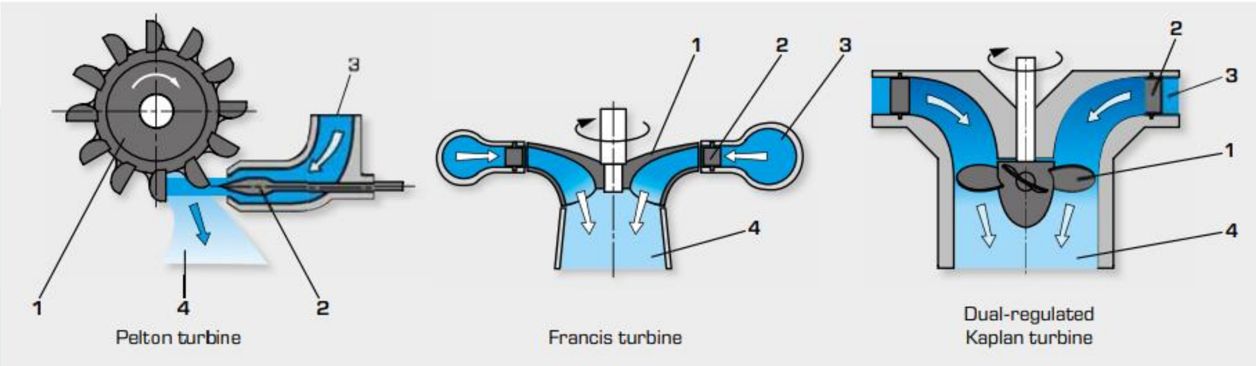
Hydropower plants - turbines



A hydroelectric generator at the Three Gorges Power Plant. China's largest hydropower project, has generated more than 150 billion kilowatt-hours of electricity since it became operational in 2003.

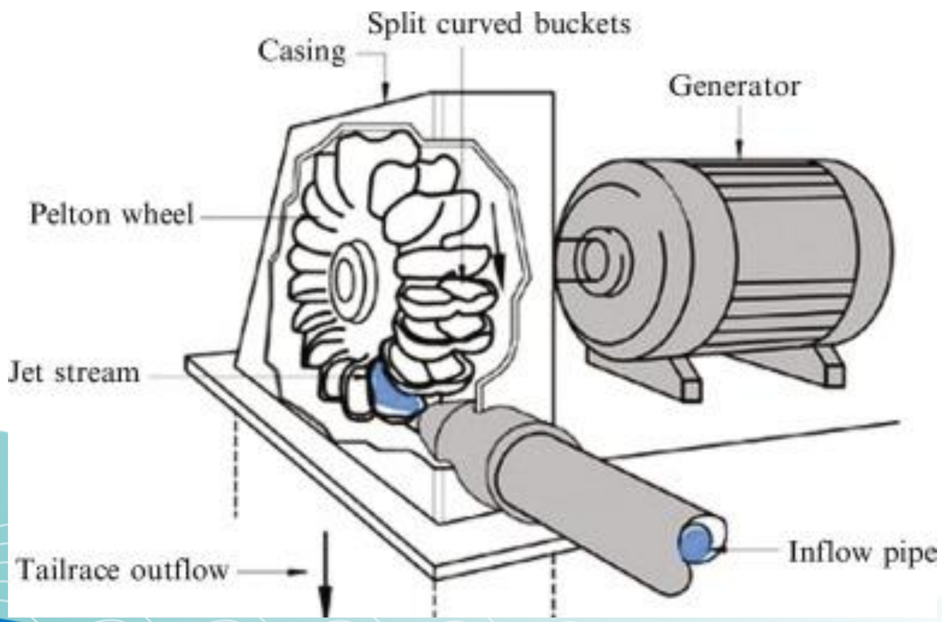
Comparison of main turbines

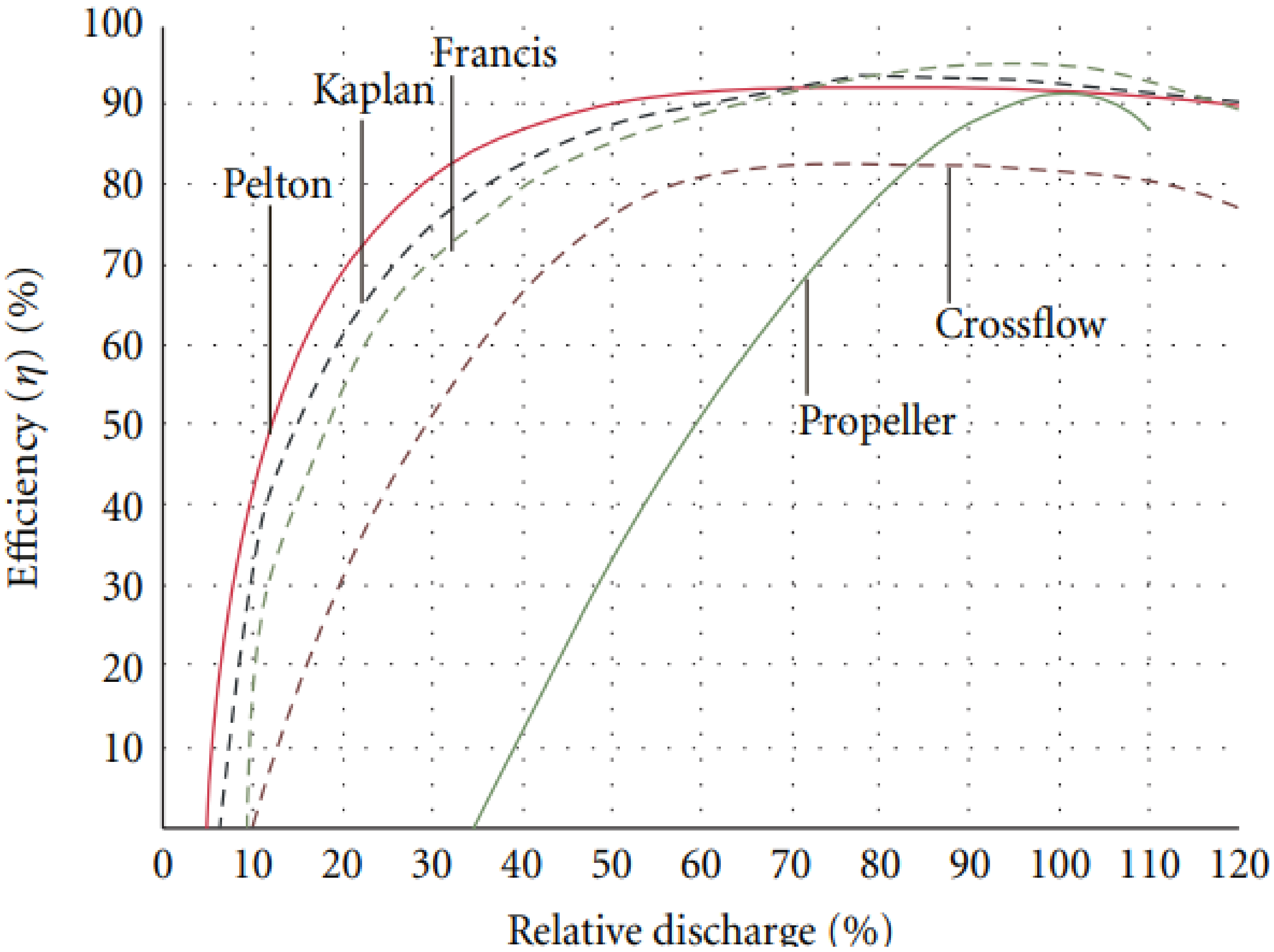
	Pelton wheel	Francis	Kaplan
Type no. ω range (rad)	0.05-0.4	0.4-2.2	1.8-4.6
Operating total head (m)	100-1700	80-500	$\leq$ 400
Maximum power output (MW)	55	40	30
Best efficiency (%)	93	94	94
Regulation mechanism	Spear nozzle and deflector plate	Guide vanes, surge tanks	Blade stagger



Hydro turbine efficiency

The hydro turbine efficiency is the efficiency with which the hydro turbine converts the mechanical power of the water into electrical power.





Source: https://www.researchgate.net/publication/258403445_Potential_of_Small-Scale_Hydropower_for_Electricity_Generation_in_Sub-Saharan_Africa/figures?lo=1&utm_source=google&utm_medium=organic