# RENEWABLE ENERGY
# HYDROELECTRICITY

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# LECTURE OUTLINE

- ❑ World Resources
- ❑ Stored Energy and Available Power
- ❑ Types of Hydro Plants
- ❑ Types of Turbines
- ❑ Discussion: Economics & Environmental impact

# *World Resources*

# Power

- The essential characteristics of a hydro site are the **effective head** ($H$), the height through which the water falls, and the **flow rate** ($Q$), the number of cubic meters of water passing through the plant per second.

- A simple approximate relationship between these two quantities and the power delivered by the water ($P$) at the *input to the turbine*, measured in kilowatts (kW):

- $P$ (kW) = $10 \times Q$ ($m^3\ s^{-1}$) $\times H$ (meters)

- The conversion of energy carried by water into electrical energy is carried out by the **turbo-generator**: a rotating turbine driven by the water and connected by a common shaft to the rotor of a generator.

# Basic Terminology

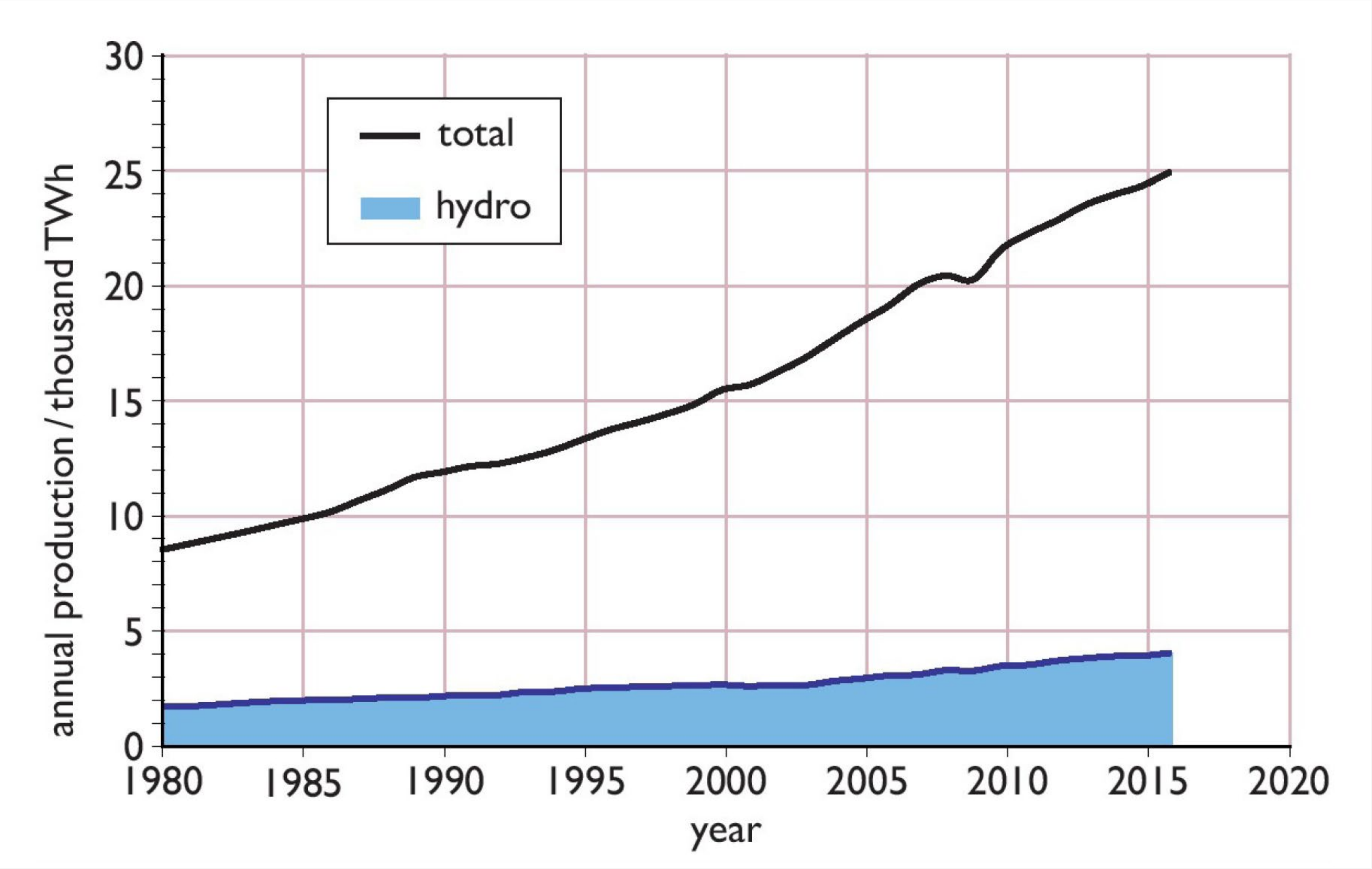
- ***The annual capacity factor*** of any plant is equal to its actual annual output divided by its output if it were to generate continuously at its full rated power, expressed as a percentage.

- If a plant has a capacity of 12 000 kW, generates 30 million kWh of electricity in a year (remembering that there are 8760 hours in a year), its capacity factor will be:

- $30 \times 10^6 / (12\,000 \times 8760) = 0.285$, or 28.5%

We express a hydro resource in terms of the total energy it delivers in the course of a year. The customary unit on the national or world scale is **terawatt hours per year, TWh $y^{-1}$** (1 TWh = 3.6 PJ, or 1 EJ = 278 TWh).

# World Electricity Production



# The World Resource

- About 20% of the 5.4 million EJ (1.1 billion TWh) of solar energy reaching the Earth's atmosphere each year is consumed in the evaporation of water.

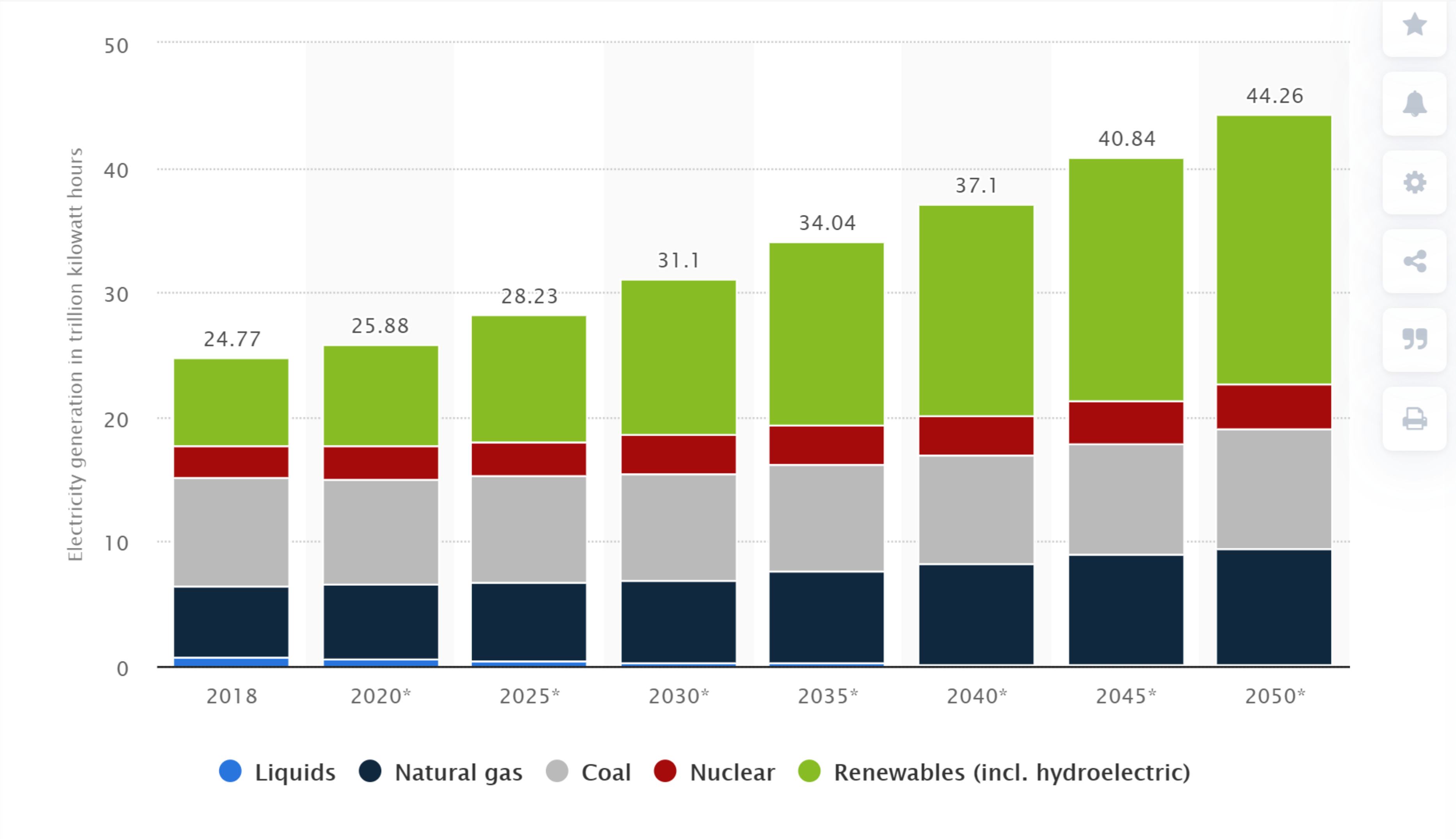
- The water vapor in the atmosphere therefore represents an enormous, constantly replaced, store of energy.

- A tiny fraction, about 200 000 TWh $y^{-1}$, reaches the Earth as rain or snow.

- Roughly one fifth of this precipitation falls on hills and mountains, descending ultimately to sea level as the world's streams and rivers.

- The 40 000 TWh $y^{-1}$ of energy carried by this flowing water can be regarded as the world's **total hydro resource**.

# World Electricity Production



# Regional Resources

**Table 6.3** Regional and world hydro potential and generated output, 2016

| | Technical potential | | Output | |
|---|---|---|---|---|
| **Region** | **Technical potential / TWh $y^{-1}$** | **% of world technical potential** | **Annual output / TWh $y^{-1}$** | **Percentage of technical potential used** |
| North America | 2420 | 15% | 680 | 28% |
| South America | 2840 | 18% | 689 | 24% |
| Europe and Eurasia | 2760 | 17% | 892 | 32% |
| Middle East | 280 | 1.7% | 21 | 7% |
| Africa | 1890 | 12% | 114 | 6% |
| Asia Pacific | 5820 | 36% | 1627 | 28% |
| World | 16 000 | | 4023 | 25% |

# National Resources

**Table 6.4** National hydro potential and contributions, 2015

| Country | Technical potential / TWh $y^{-1}$ | Annual output / TWh $y^{-1}$ | Installed capacity * / GW | Average capacity factor | Percentage of nation's electricity |
|---|---|---|---|---|---|
| China | 2500 | 1115 | 296 | 43% | 19% |
| Canada | 830 | 378 | 79 | 55% | 58% |
| Brazil | 1250 | 360 | 92 | 45% | 62% |
| USA | 1340 | 247 | 79 | 36% | 6% |
| Russia | 1670 | 170 | 49 | 40% | 16% |
| Norway | 240 | 138 | 29 | 54% | 95% |
| India | 660 | 133 | 42 | 36% | 10% |
| Japan | 140 | 84 | 22 | 44% | 8% |
| Venezuela | 260 | 76 | 15 | 58% | 59% |
| Sweden | 130 | 75 | 16 | 54% | 46% |
| Turkey | 220 | 67 | 26 | 29% | 26% |
| Vietnam | 120 | 57 | 15 | 43% | 36% |
| France | 100 | 54 | 18 | 34% | 9% |
| Italy | 65 | 46 | 22 | 24% | 16% |
| Switzerland | 43 | 38 | 14 | 31% | 54% |
| Austria | 75 | 37 | 8 | 53% | 57% |

# *Stored Energy and Available Power*

# Potential Energy

potential energy (joules) = $M$ (kg) × g × $H$ (m)

g =9.81 m $s^{-2}$ ~ 10 m $s^{-2}$

*stored* energy (joules)= 1000 x $V$ x g x $H$

1 kilowatt-hour = 3.6 MJ

Storing 1 kWh requires raising 1 cubic meter of water through a height of 360 meters.

# Pumped Storage

- The need to provide rapid short-term back-up for a period of several hours is thus vital to prevent power cuts
- Installed capacity worldwide having grown from 78 GW in 2005 to 150 GW in 2016 – equivalent to one seventh of the world's total hydro capacity

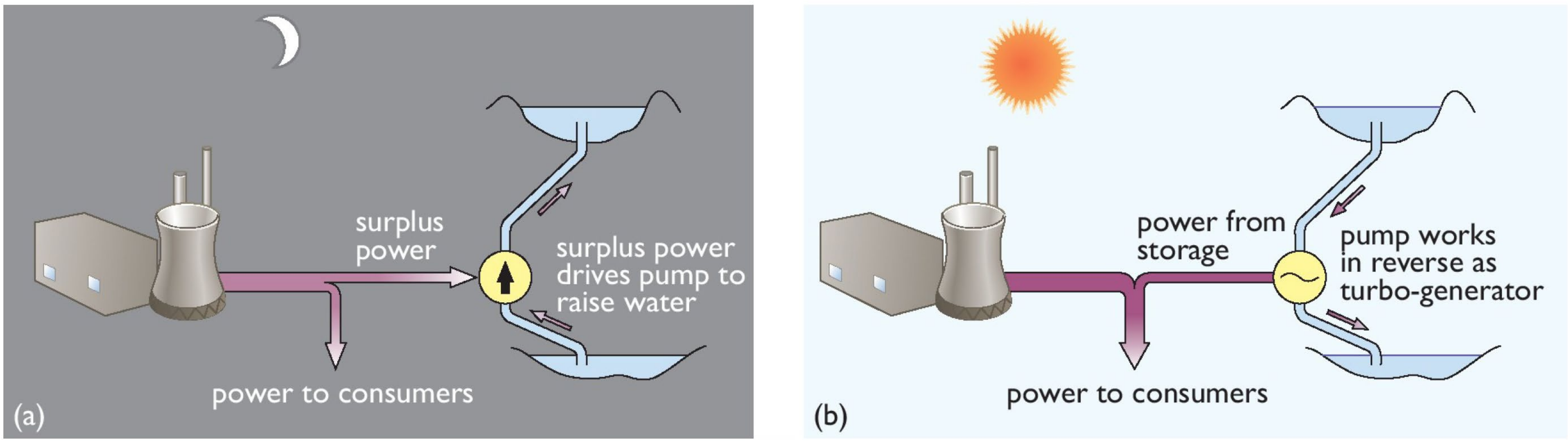
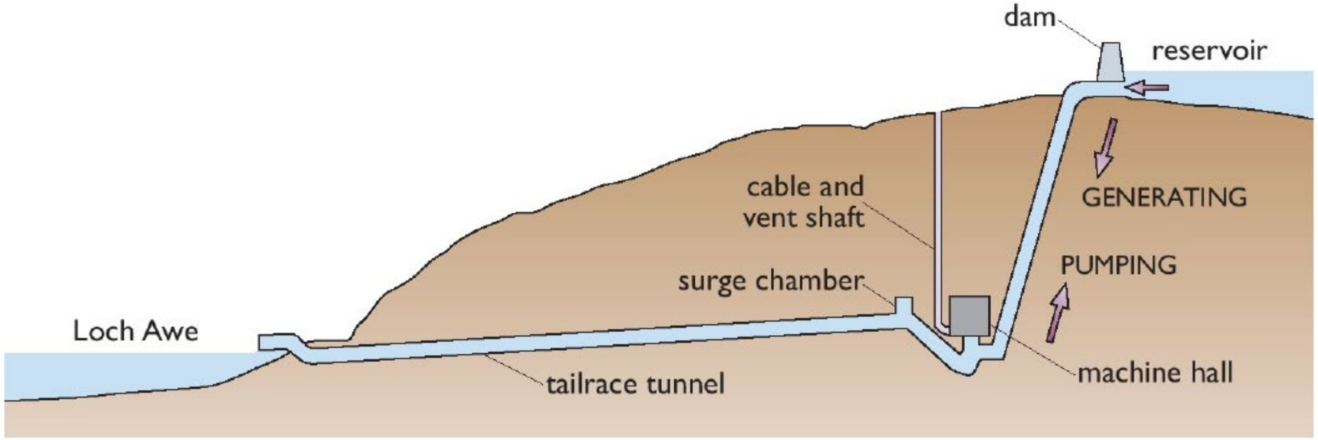



**Figure 6.7** Pumped storage system: (a) at time of low demand, (b) at time of high demand

# Pumped Storge to meet short-term demand




(a)

(b)

# Power, head, and flow rate

$$P\,(\text{watts}) = 1000 \times Q\,(\text{m}^3\ \text{s}^{-1}) \times \text{g} \times H\,(\text{m})$$

- The water falling through a pipe will lose some energy due to frictional drag and turbulence, and the effective head will thus be less than the actual, or gross head. It varies from 75-95%.
- The **efficiency** – $\eta$ - the ratio of the output power to the input power, usually expressed as a percentage – is always less than 100%.

$$P = 1000 \times \eta \times Q \times \text{g} \times H$$

If we now express *P* in kilowatts, and use the approximation g = 10 m $s^{-2}$, we obtain a very useful, simple expression

$$P\,(\text{kW}) = 10 \times \eta \times Q\,(\text{m}^3\ \text{s}^{-1}) \times H\,(\text{m})$$

# Example of Small versus Large-scale Hydro

**BOX 6.4 Available power**

As examples of power calculations, we can consider two systems, each with a plant efficiency of 83%, but of very different sizes.

The first site is a mountain stream with an effective head of 25 metres and a modest flow rate of 600 litres a minute, which is 0.010 cubic metres per second. Using Equation (4), we find that the power output will be

$$P = 10 \times 83\% \times 0.010 \times 25 = 2.075 \text{ kW}$$

In contrast, suppose that the effective head is 100 m and the flow rate is 6000 cubic metres per second – roughly the total flow over Niagara Falls. The power is now

$$P = 10 \times 83\% \times 6000 \times 100 = 4.98 \text{ million kWh, or nearly 5 GW}$$

# *Hydro Plant Classification*

# Types of Hydro Plants

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

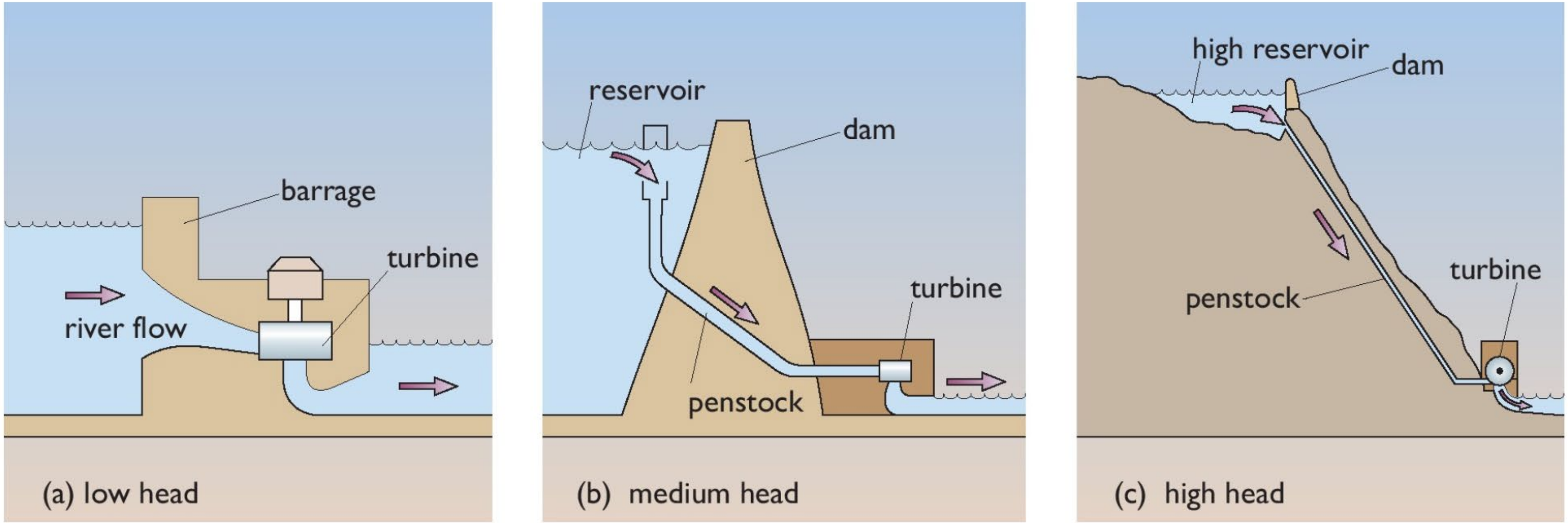


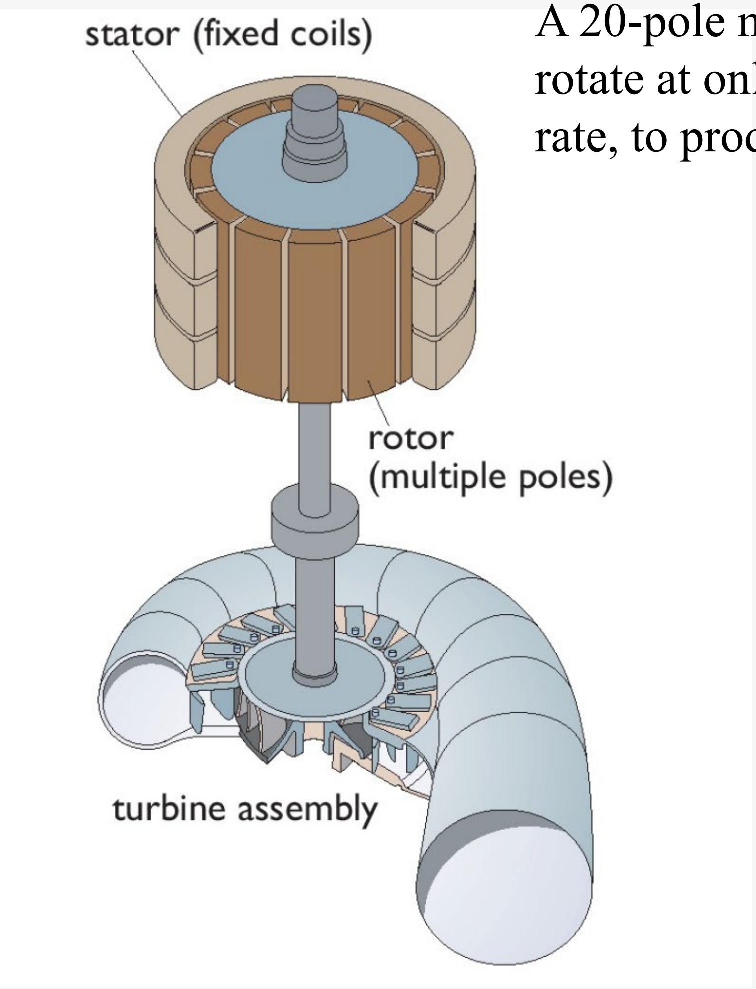

**Figure 6.13** Types of hydroelectric installation

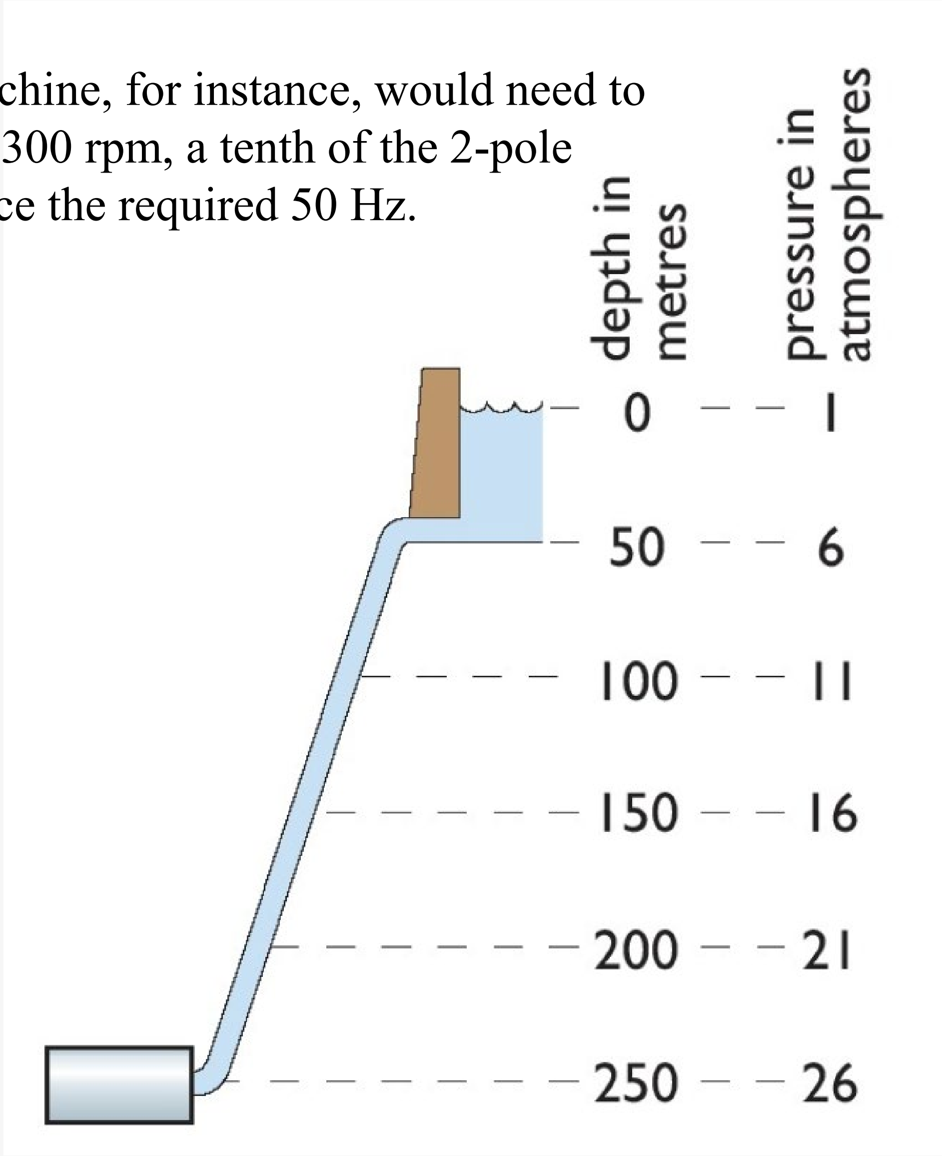
# The Hoover Dam

**Figure 6.14** The Hoover Dam, 1936. This dam on the Colorado River (originally called the Boulder Dam) is 220 metres high and its reservoir, Lake Mead, holds 35 billion cubic metres of water. The 2.1 GW power plant is at the foot of the dam.

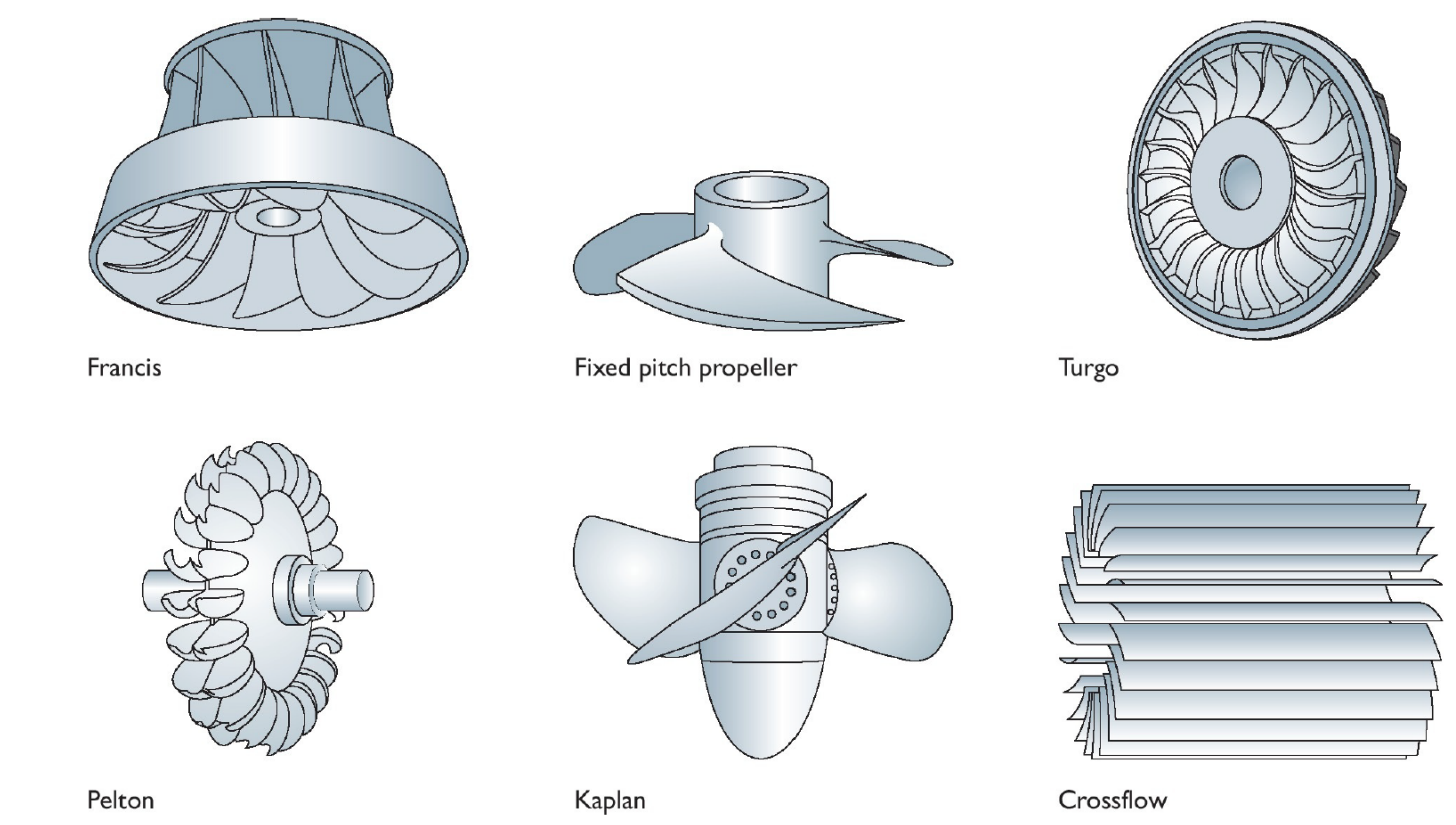
# Head and Pressure – Running Turbines

A 20-pole machine, for instance, would need to rotate at only 300 rpm, a tenth of the 2-pole rate, to produce the required 50 Hz.



# Types of Turbines



# Francis Turbine

- Francis turbines (Figures 6.17 to 6.20) are by far the most common type in present- day medium- or large-scale plants, being used in locations where the head may be as low as 2 m or as high as 200 m. They are radial-flow turbines.

- As the Francis turbine is completely submerged, it can run equally well with its axis horizontal or vertical.

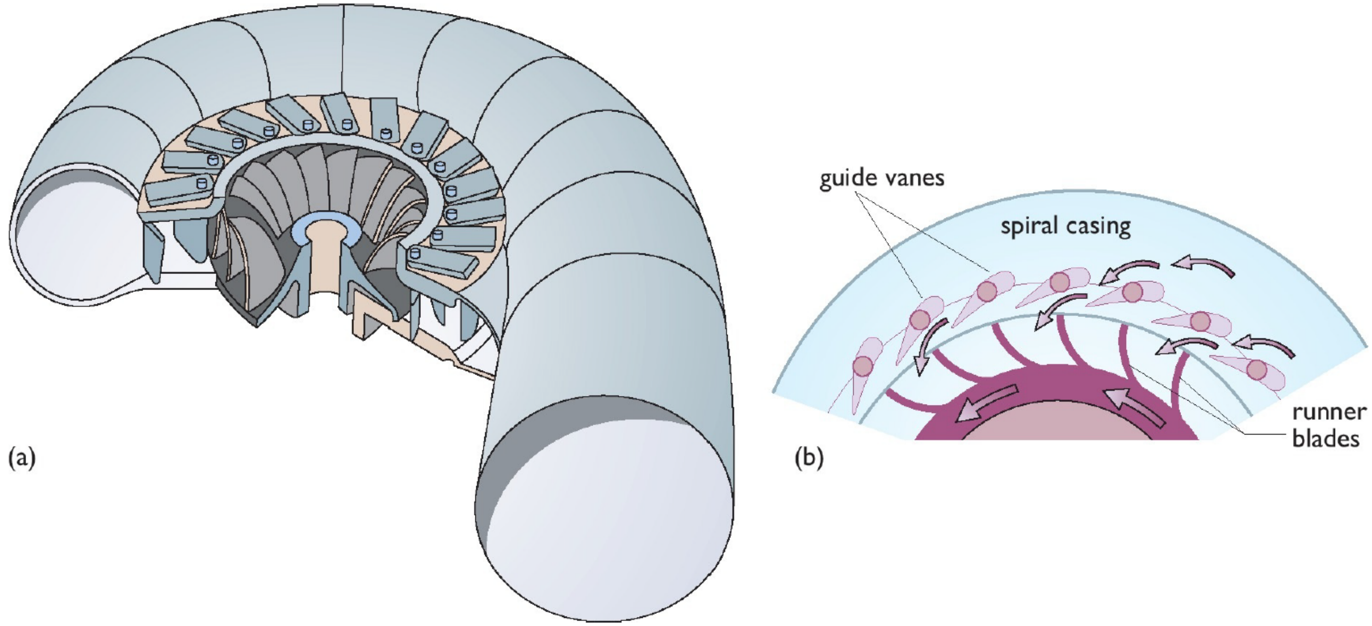


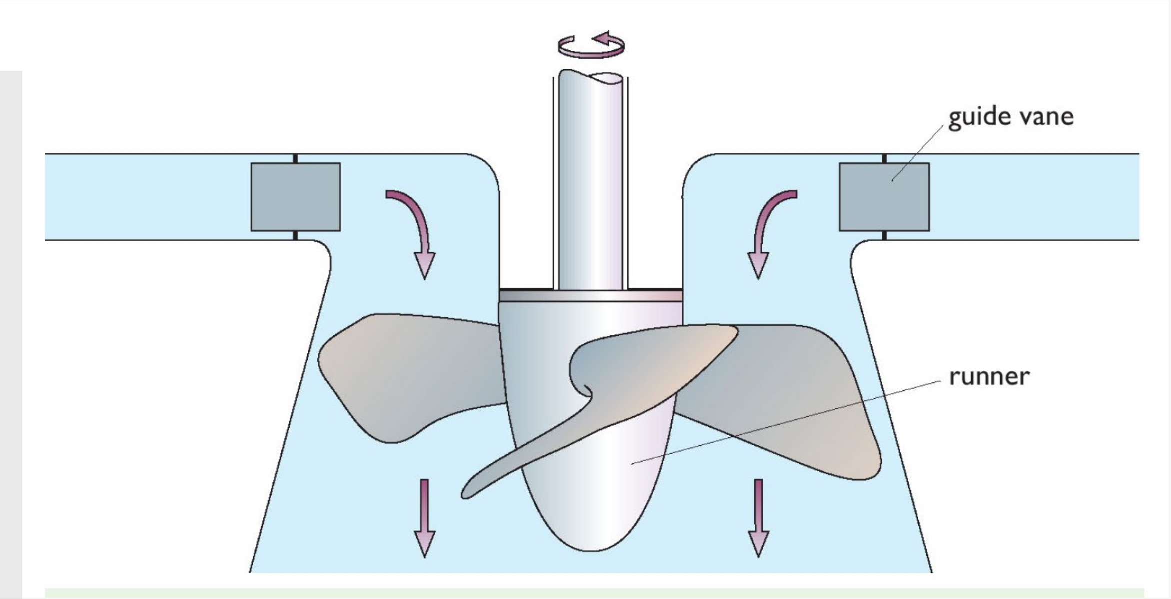

**Figure 6.20** Structure of a Francis turbine, showing the central runner blades, the pivoting guide vanes and the surrounding volute

# Propeller – or Axial Flow Turbines

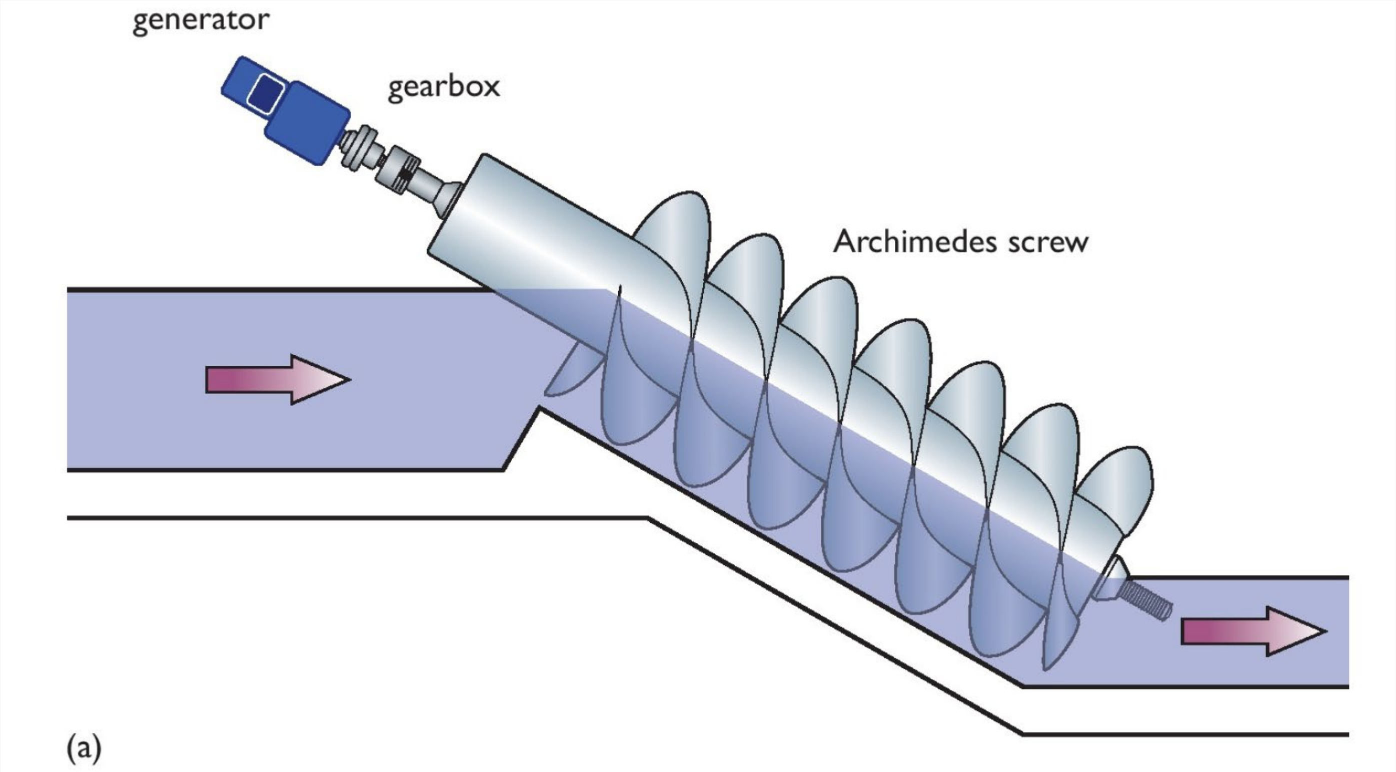
- If the head is low, a large volume flow is needed for a given power. But a low head also means a low water speed, and these two factors together mean that a much larger input area is required.

- This limits the use of Francis turbines.  The alternative is an axial turbine, or propeller.

They have the advantage over radial-flow turbines in that it is technically simpler to improve the efficiency by varying the angle of the blades when the power demand changes. Axial-flow turbines with this feature are called Kaplan turbines



# *Archimedes Screw*




- The Archimedes screw can be thought of as an extended propeller in a trough.
- It is claimed that, given an adequate gap between the blades, this technology is 'fish friendly' allowing fish to pass right through the turbine unharmed

# Pelton Wheels

- For sites of the type shown in Figure 6.13(c), with heads above 250 meters, the Pelton wheel is the preferred turbine.

- It is, in contrast to the reaction turbines, an impulse turbine.

- One important difference between the turbine types is that whereas a reaction turbine runs fully submerged and with a pressure difference across the runner, impulse turbines essentially operate in air at normal atmospheric pressure.

- A Pelton wheel is basically a wheel with a set of double cups or 'buckets' mounted around the rim. A high-speed jet of water, formed under the pressure of the high head, hits the splitting edge between each pair of cups in turn as the wheel spins.

- The water passes round the curved bowls, and under optimum conditions gives up almost all its kinetic energy.

- The efficiency of a Pelton wheel is greatest when the speed of the cups is half the speed of the water jet.

# Structure of the Pelton Wheel

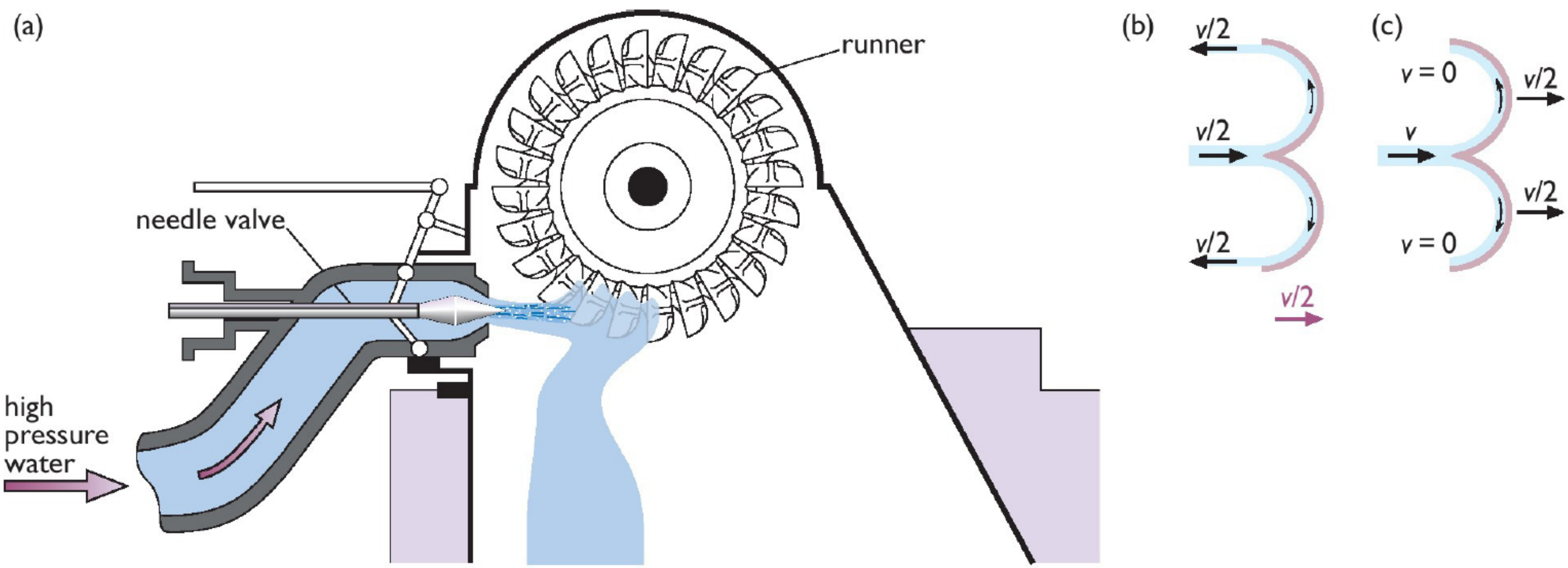



**Figure 6.24** Structure of a Pelton wheel turbine: (a) vertical section, (b) water flow as seen from moving cup, (c) actual motion of water and cup

# Equations for effective head, water speed and flow rate

$$\text{kinetic energy} = \frac{1}{2}Mv^2$$

So if all the lost potential energy is converted into kinetic energy, we have:

$$\frac{1}{2}Mv^2 = MgH$$

so $v^2 = 2gH$ and

$$v = \sqrt{(2gH)} \qquad (5)$$

If this water flows as a jet with a circular area of A square metres, the volume flowing out in each second $Q$ in $m^3\ s^{-1}$ will be equal to $A$ times $v$. So the volume flow rate for an effective head $H$ is given by:

$Q = A \times \sqrt{(2gH)}$ cubic metres per second

$$P\ (\text{watts}) = 1000 \times Q \times g \times H$$

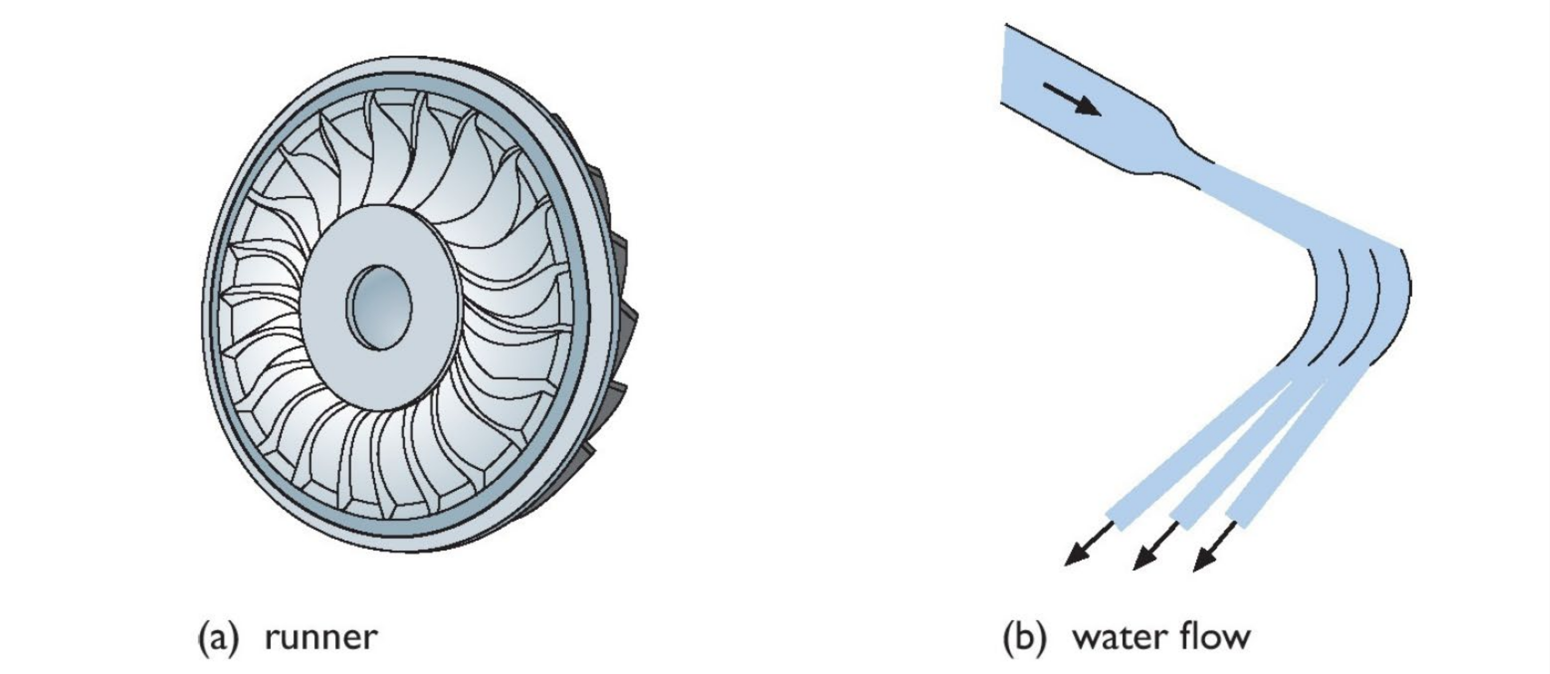
so substituting for Q we find that:

$$P = 1000 \times A \times \sqrt{(2gH)} \times g \times H$$

Using the approximate value of g ($10\ m\ s^{-2}$), the power in kilowatts becomes

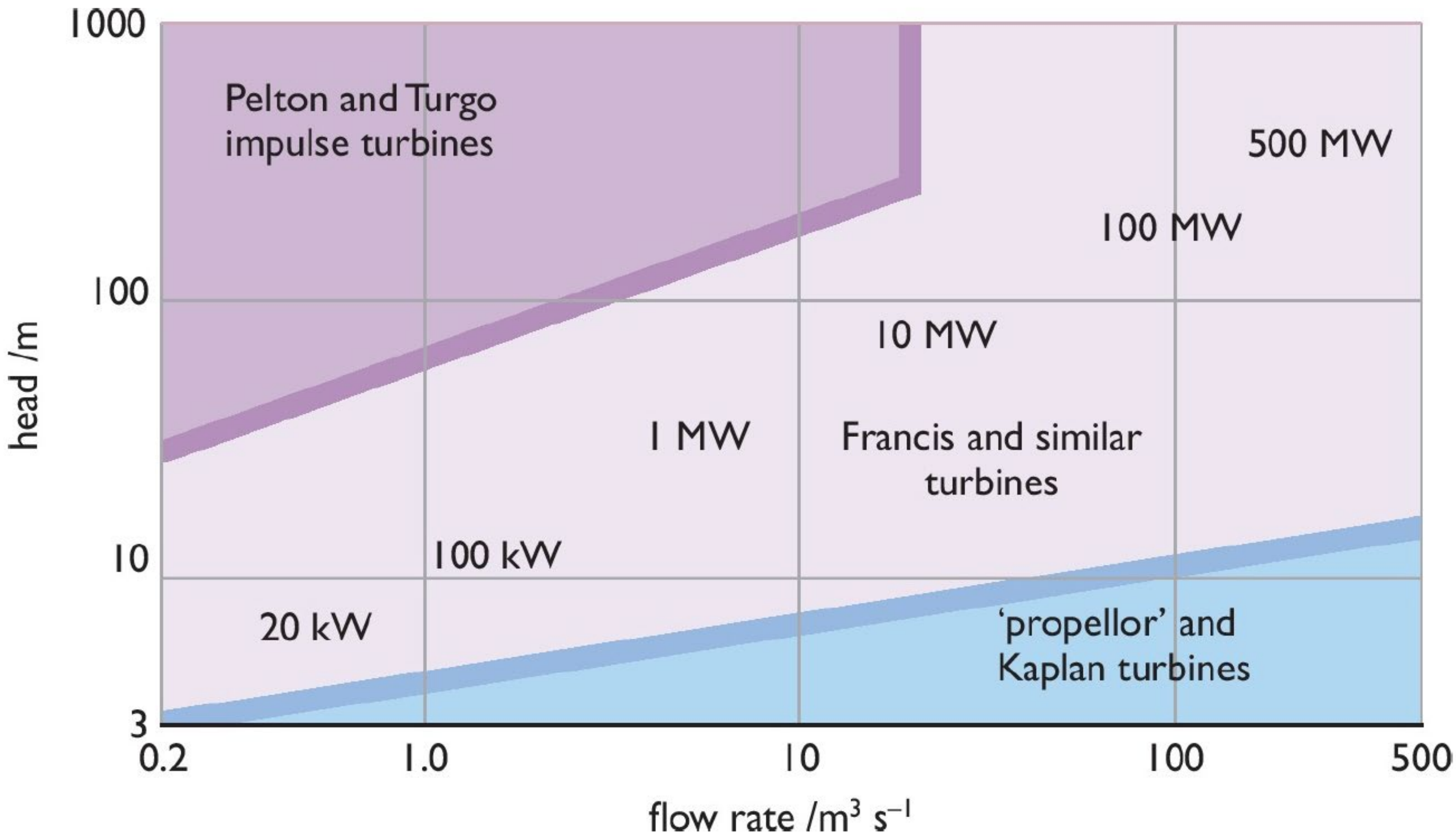
$$P\ (\text{kW}) = 45A\sqrt{(H^3)}$$

# *Turgo & cross-flow turbines*




- A variant on the Pelton wheel, developed in the 1920s.
- The double cups are replaced by single, shallower ones, with the water entering on one side and leaving on the other.
- The water enters as a jet at a low angle to the plane of the turbine, striking the cups in turn, so this is still an impulse.
- However, its ability to handle a larger volume of water than a Pelton wheel of the same diameter gives it an advantage for power generation at medium heads.

# Ranges of application of various turbines



# *Discussion on Economics & Environmental Impact*

# *Discussion Topics*

- **Hydrological effects** – water flows, groundwater, water supply & irrigation.

- **Other physical effects of large hydro plants**: Dam failures, plant failures, silt, fish, methane, .

- **Social effects**: Aswan dam in Egypt, and the three gorges dam on the Yangze River (China).