John Andrews & Nick Jelley

Lecture 6:

Hydropower, tidal power, and wave power

Waterwheels

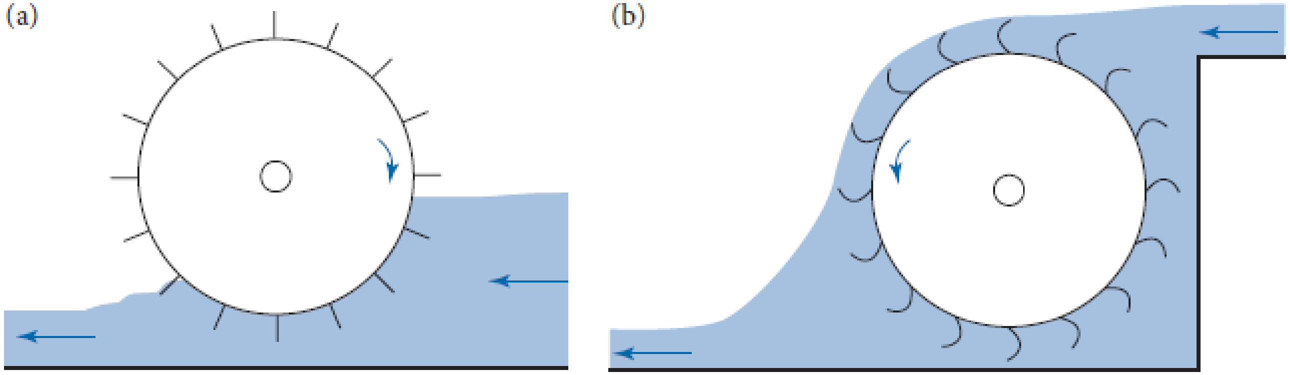


Fig. 6.1 (a) Undershot and (b) overshot waterwheels.

Waterwheels were common in Western Europe by AD1000. **5000 recorded in Domesday Book (1086).**

Undershot waterwheels very inefficient. **Overshot** designs around 66% efficient.

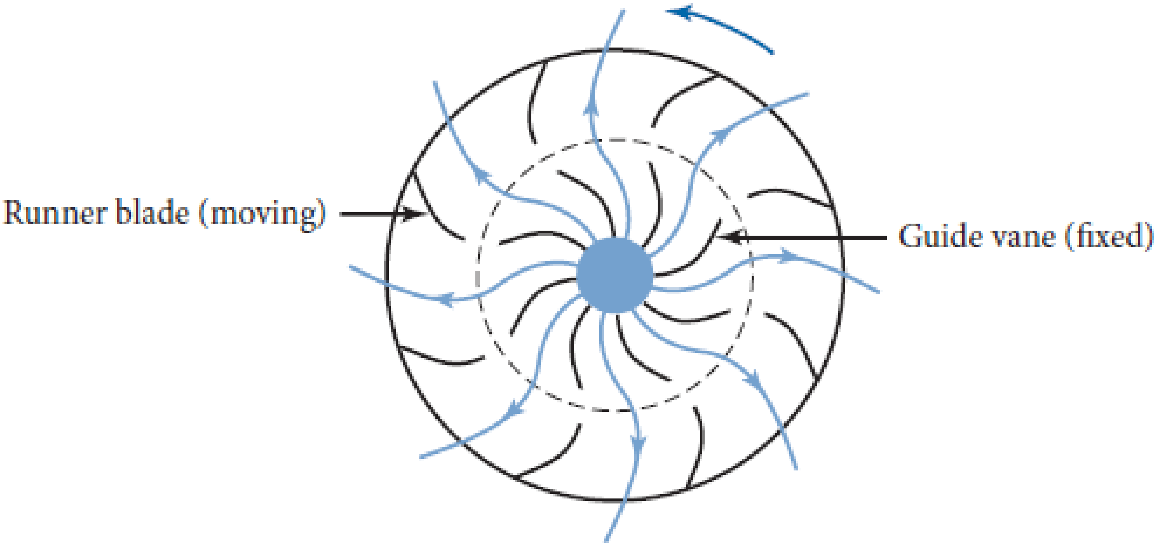


Fig. 6.2 Fourneyron water turbine (schematic).

Breakthrough in 1832 with **Fourneyron turbine**, with fixed guide vanes and moving runner blades. 80-90% efficient. Moreover, head not limited to diameter (as in overshot wheels) since water contained in a pipe.

Hydropower

Hydropower is largest renewable source of power (450 GWe in 2015). Plant life over 50 years.
3 types of system: (1) **dams/reservoirs**, (2) **run-of-river**, (3) **pumped storage**

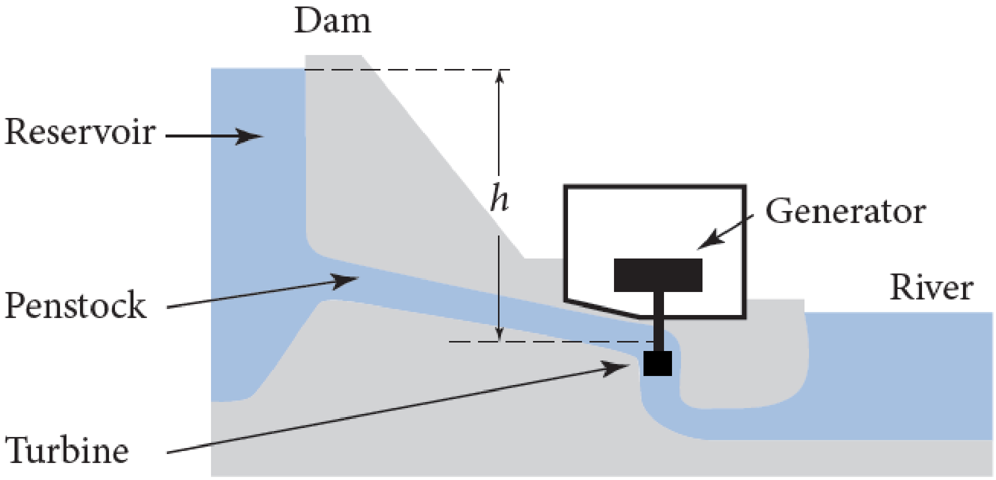
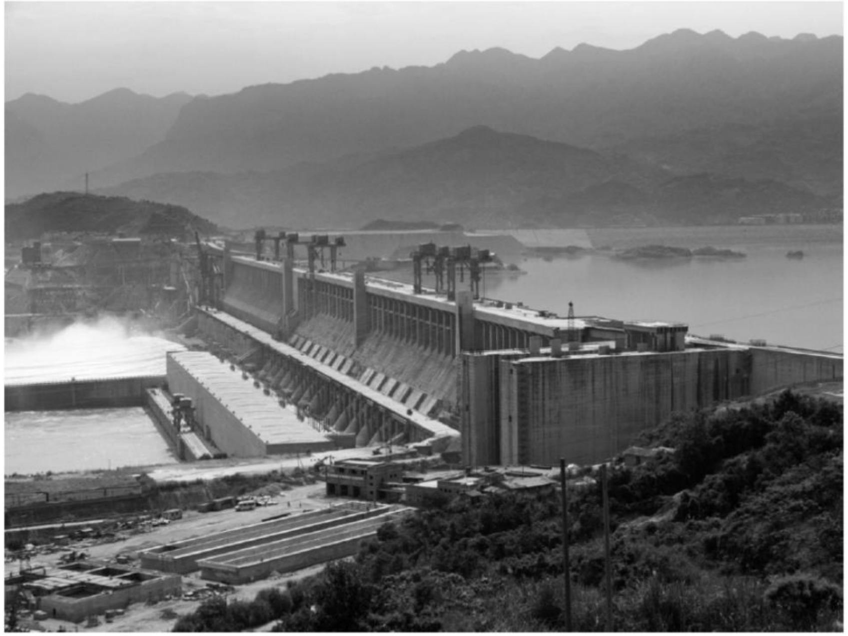


Fig. 6.3 Hydroelectric plant.



Three Gorges Dam in China

Credit: www.stema-systems.nl

Power output of dam $\boxed{P = \eta \rho g h Q}$

(Note dependence on product ***hQ***)

e.g. efficiency $\eta = 1$, $\rho = 10^3$ kg m^{-3},
$Q = 20$ m^3 s^{-1}, $g = 10$ m s^{-2}, gives
$P = 10$ MW

Impulse turbines and reaction turbines

Impulse turbines are used for large head *h* and low volume flow rate *Q* situations. Momentum of water jets is transferred to turbine blades.

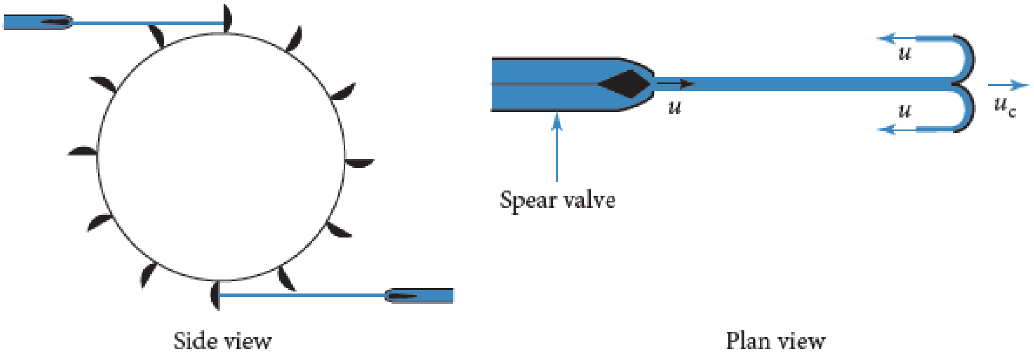


Fig. 6.5 Impulse turbine (Pelton wheel).

Pelton wheel maximises momentum transfer by designing cups so that reflected jet is in opposite direction to incident jet. Maximum power output is

$$\boxed{P_{\max} = \tfrac{1}{2}\rho Q u^2}$$

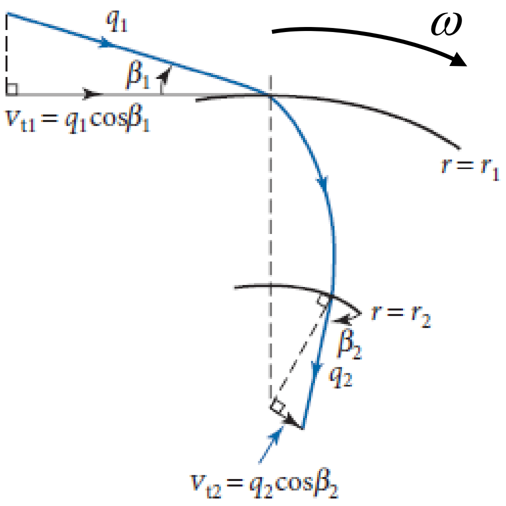
Reaction turbines are used for lower head *h* but larger *Q* situations, e.g. **Francis turbine** (spiral annulus) **Kaplan turbine** (propeller shape).

Power output of reaction turbine is given by **Euler's equation**

$$P = (\text{mass flow rate}) \times (\text{energy per unit mass})$$

$$= \rho Q \left(u_1 q_1 \cos\beta_1 - u_2 q_2 \cos\beta_2 \right)$$, where $u = \omega r$

(Note: power depends only on inlet and outlet flows, not on flow inside the turbine.)



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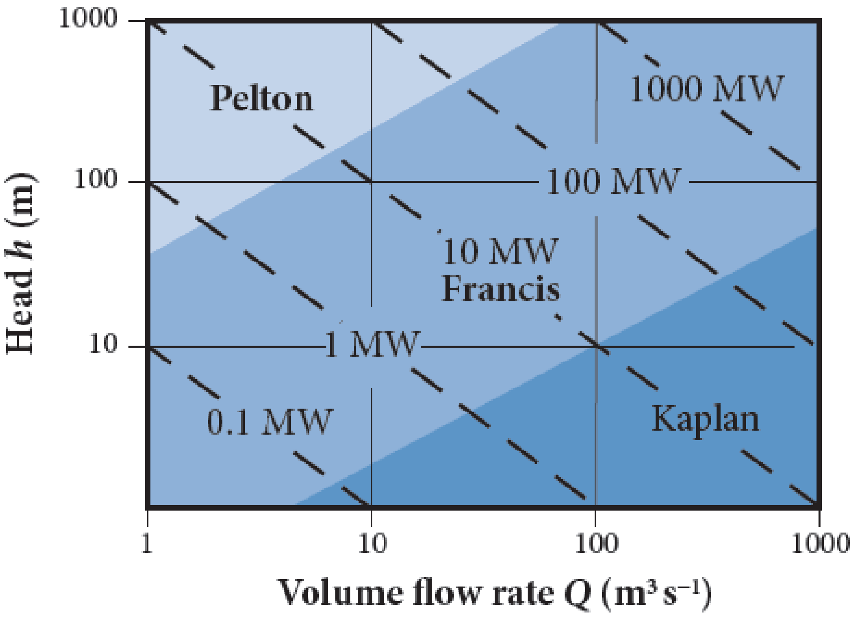
Hydropower (contd.)



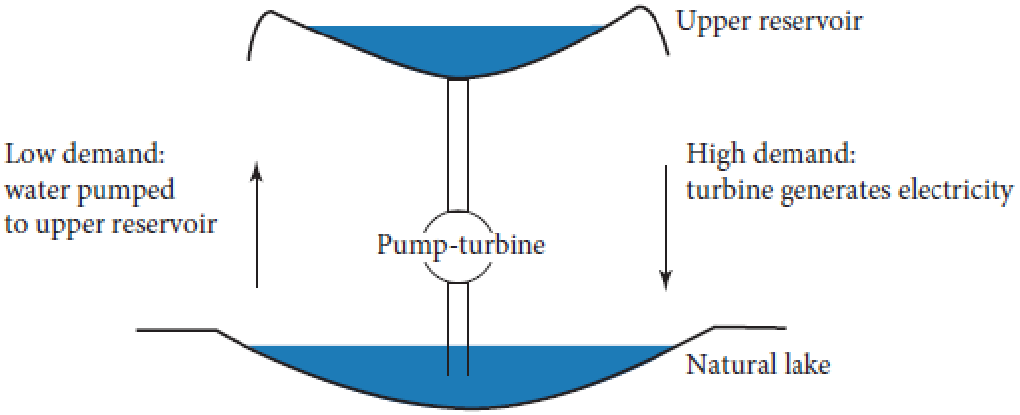


Fig. 10.6 Pumped storage.

Choice of turbine depends on head *h* and volume flow rate *Q*.

In 2015, **pumped storage** accounted for 97% of energy storage and generated 145 GW. Fast response to demand; provides back-up to variable sources like solar power and wind power.

Advantages of hydropower: long plant life, low carbon footprint

Disadvantages of hydropower: large capital cost, relocation of population, dam collapse

Present and future of Hydropower

Existing installations by country:

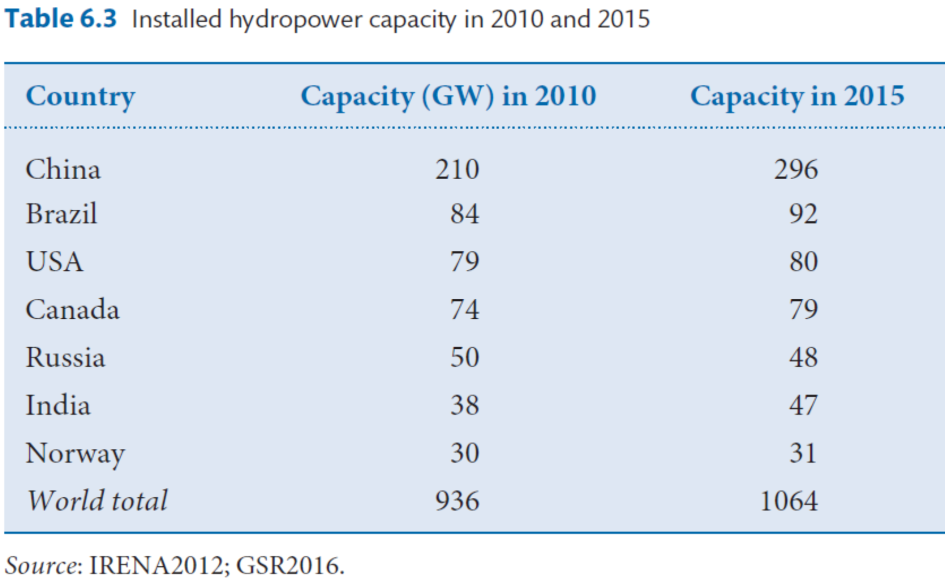
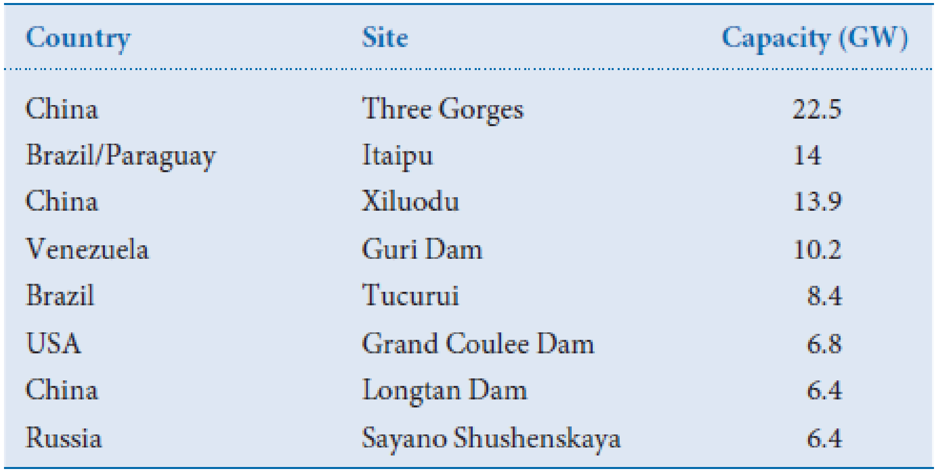


Table 6.3 Installed hydropower capacity in 2010 and 2015

Country	Capacity (GW) in 2010	Capacity in 2015
China	210	296
Brazil	84	92
USA	79	80
Canada	74	79
Russia	50	48
India	38	47
Norway	30	31
World total	936	1064

Source: IRENA2012; GSR2016.

Largest sites:



Country	Site	Capacity (GW)
China	Three Gorges	22.5
Brazil/Paraguay	Itaipu	14
China	Xiluodu	13.9
Venezuela	Guri Dam	10.2
Brazil	Tucurui	8.4
USA	Grand Coulee Dam	6.8
China	Longtan Dam	6.4
Russia	Sayano Shushenskaya	6.4

- Estimated global technical potential = 15 000 TWh (1700 GWe continuous) at 45% capacity.
- Untapped: Asia 6000 TWh, Latin America 2000 TWh, N America 1000 TWh, Africa 1000 TWh
- Only 25% of global hydropower potential exploited to date
- IEA predicts global hydropower capacity to increase to almost 2000 GW and that of pumped storage by 3-5 fold to 400-700 GW by 2050

Tidal power

2 high tides and 2 low tides around the Earth at any instant. Interval between high tides = 12 hours 25 mins. Typical tidal range = 0.5-1.0 m.

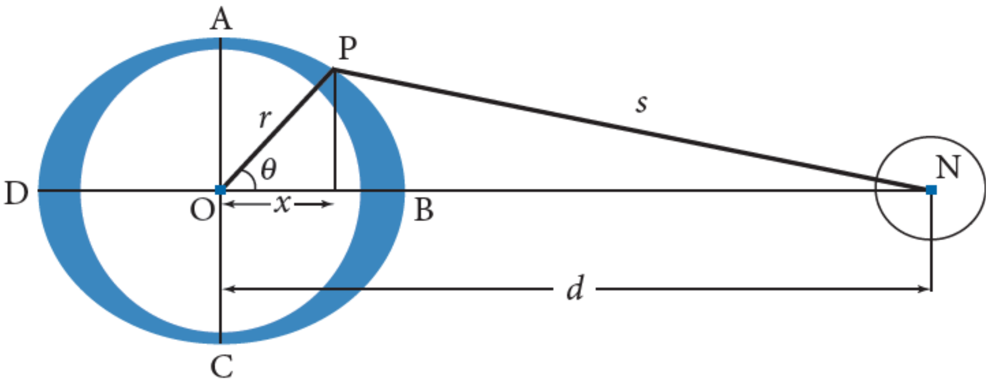


Fig. 6.10 Tidal effects due to the Moon (not to scale).

Height $h(\theta) = h_{\max}\left(\frac{3}{2}\cos^2\theta - \frac{1}{2}\right)$

$$\text{where } h_{\max} = \frac{mr^4}{Md^3}$$

$$\frac{m}{M} = 0.0123,\ r = 6378\text{ km},$$

$$d = 384\,400\text{ km, gives } h_{\max} \approx 0.36\text{ m}$$

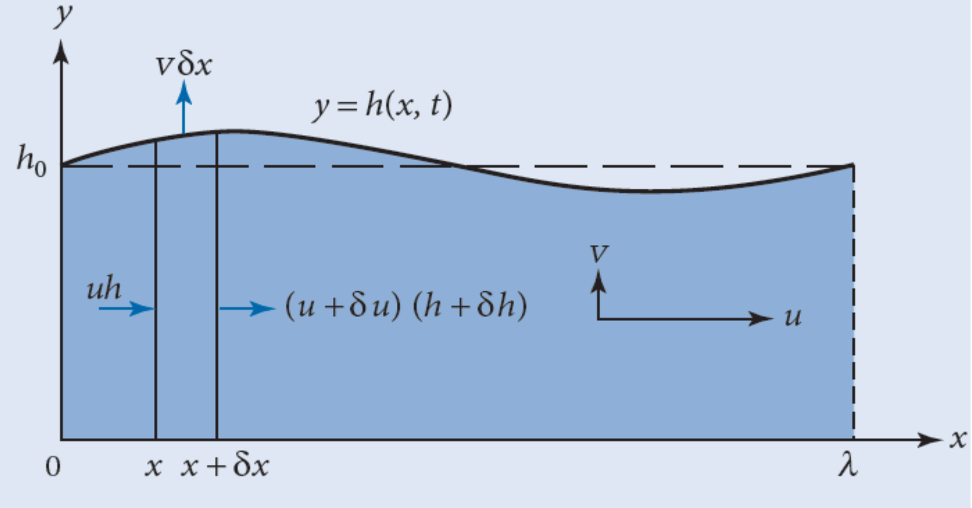


Fig. 6.11 Shallow water wave.

Tidal waves are 'shallow' in that their mean depth h_o << wavelength, λ. Speed of tidal wave Is given by

$$\boxed{c = \sqrt{gh_o} \approx 200\text{ m s}^{-1}}$$

(slower than speed of rotation of Earth)

Tidal Barrage

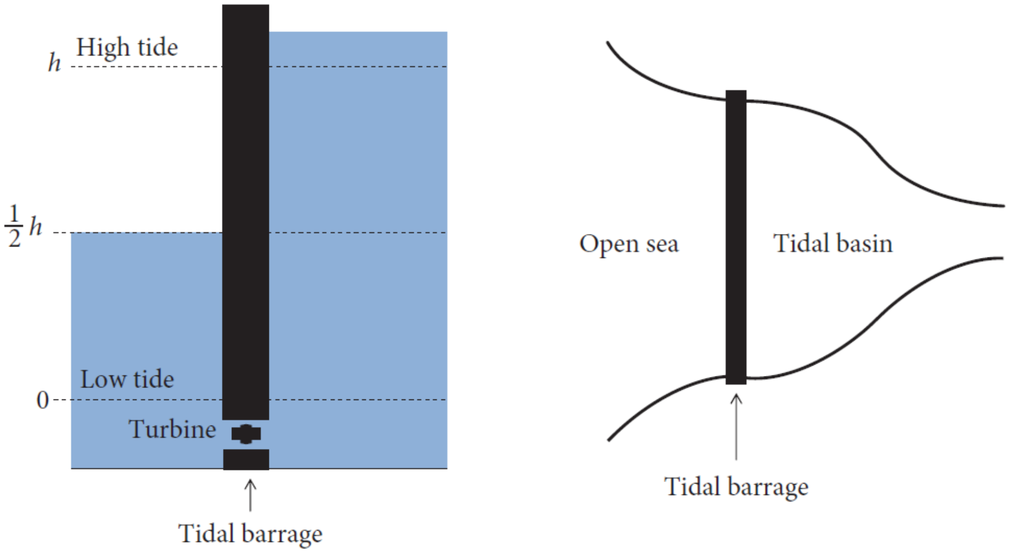


Fig. 6.14 Tidal barrage, with the height in the tidal basin raised by pumping.

First tidal power plant: La Rance (France) in 1966, 240 MW, 24 Kaplan turbines. More recent Sihwa, in South Korea.

Capital cost of tidal barrage is very high, but there are plans for smaller schemes, e.g. Swansea Lagoon.

Average power output

$$\boxed{P_{\text{ave}} \approx \frac{\rho g A h^2}{4T}}$$

Tidal range in Bay of Fundy (Nova Scotia) *h* = 13 m, Bristol Channel (UK) *h* = 12 m. **Resonant enhancement**.

Sihwa tidal barrage, 254 MW

Credit: Topic Images Inc./ Getty

Tidal Steam Plants

Mygen18m1.5 MW turbine in Pentland Firth, Scotland. Array by 2020 with output ~ 400 MW

Tidal stream plants extract kinetic energy from strong tidal currents between islands, e.g. SeaGen (Northern Ireland) generates 1.2 MWe with capacity factor of 75-80%.

For isolated turbine, maximum fraction extractable is given by **Betz limit**: 59% (see Wind Power lecture), but for turbines in a channel

Maximum average power $\boxed{P_{\max} = \gamma \rho g a Q_{\max}}$

where γ *~0.22*

Note similarity to power from dam, $P = \eta \rho g h Q$

Impact of tidal power: Negatives: (1) blocks shipping, (2) turbines kill fish, (3) changes tidal range downstream, (4) changes water quality,
Positives: (1) renewable, (2) benefits local economy, (3) tourist industry

Outlook for tidal power: large global resource (2.5 TW) but only 3%, 75 GW, is economically feasible with barrages, with tidal ranges of 5 m or more, and capital cost is very high. However, tidal stream plants have better prospects, being cheaper, unobtrusive and have predictable output.

Essentials of fluid mechanics

A basic knowledge of fluid mechanics is useful to understand how some wave power and wind power devices work.

Stream-tube: any elemental mass in the fluid follows notional curve which is parallel to the direction of flow; stream-tubes can be seen in wind tunnels using smoke particles

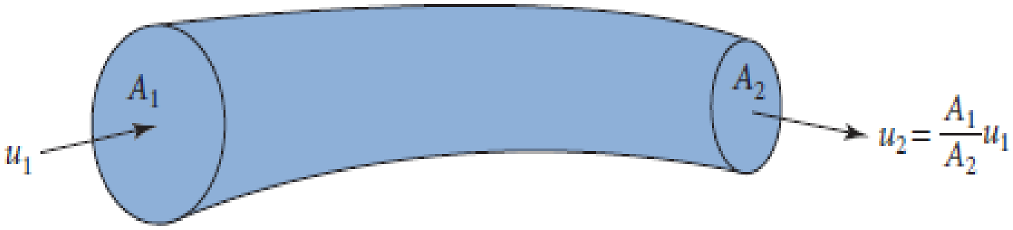


Fig. 2.9 Stream-tube.

Mass continuity: mass flow rate through a stream-tube is constant for steady flow, so

$$\boxed{\rho u A = \text{constant}}$$

Hence, speed *u* is inversely proportional to the cross sectional area *A* of the stream-tube.

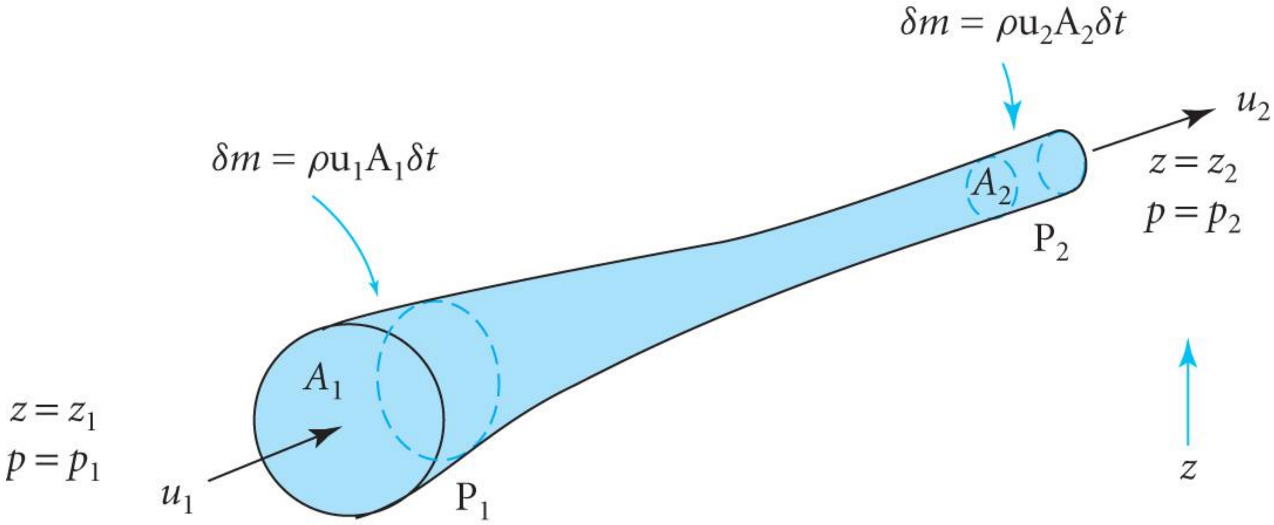
Bernoulli's equation: for steady flow through a stream-tube, the total energy is constant. Ignoring gravitational effects, it implies that the pressure drops as the speed of a fluid increases, and vice versa.

$$\boxed{\tfrac{1}{2}u^2 + \frac{p}{\rho} + gz = \text{constant}}$$

Derivation of Bernoulli’s equation

Assume steady flow, no friction, no thermal effects

Mass flow rate,
Q = constant
$= \rho A_1 u_1 = \rho A_2 u_2$



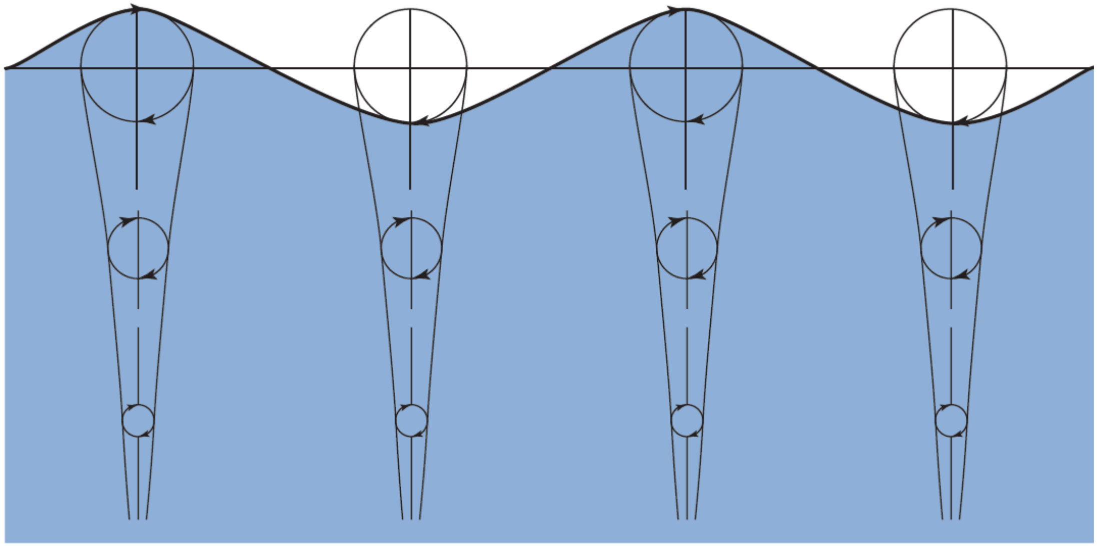
By energy conservation,
rate of work done by pressure + rate of loss of potential energy = rate of gain of kinetic energy, so

$$(p_1 A_1 u_1 - p_2 A_2 u_2) + Q\,g(z_1 - z_2) = ½\,Q\,(u_2^2 - u_1^2)$$

or $½\,Q\,u_1^2 + p_1 A_1 u_1 + Q\,g\,z_1 = ½\,Q\,u_2^2 + p_2 A_2 u_2 + Q\,g\,z_2$

Dividing by $Q = \rho A_1 u_1 = \rho A_2 u_2$ yields $\boxed{\frac{1}{2}u^2 + \frac{p}{\rho} + gz = \text{constant}}$

Surface waves on the sea



Most waves on surface of the sea are caused by wind. Streamlines are closer together over wave crests and the air moves faster and the pressure drops, by Bernoulli's theorem. Hence the water surface rises.

For waves on deep water, particles move in circles, which decrease in radius with depth. About 80% of the energy is within a depth of a quarter of a wavelength, λ.

Wave speed $\boxed{c = \sqrt{\frac{g\lambda}{2\pi}}}$ (dispersive waves)

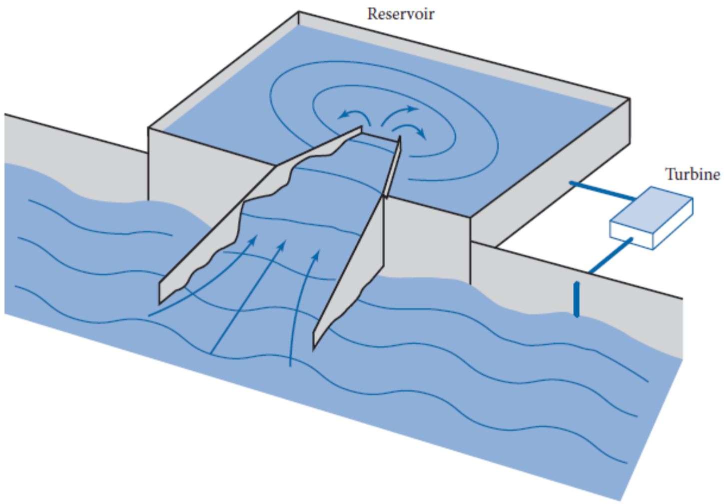
Power of wave per unit width of wave-front $\boxed{P = \tfrac{1}{4}\rho g a^2 \sqrt{\frac{g\lambda}{2\pi}}}$

In mid-ocean, power of wave per unit width of wave-front is 30-70 kW m^{-1}

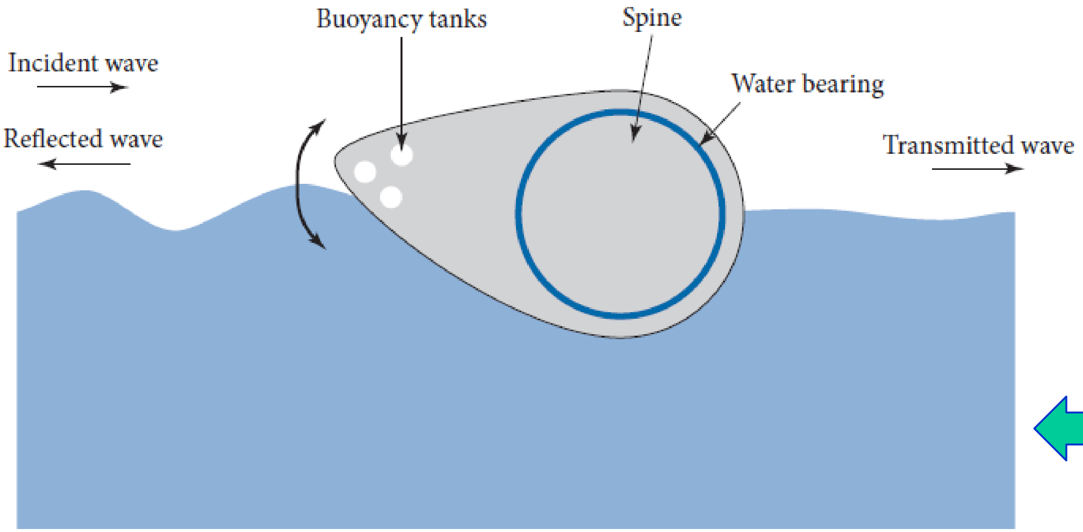
Wave power technology

Wave power research was boosted in the 1970s by the oil price shocks. Numerous designs were proposed but most were not developed. The main issues with any wave power device are

- Survivability in storms,
- Vulnerability of moving parts to seawater
- Capital cost
- Operational costs
- Cost of connection to the electricity grid



Tapered channel (TAPCHAN). Waves spill over ramp, water drains back through low head Kaplan turbines



Salter Duck, never built to full scale

OXFORD
UNIVERSITY PRESS

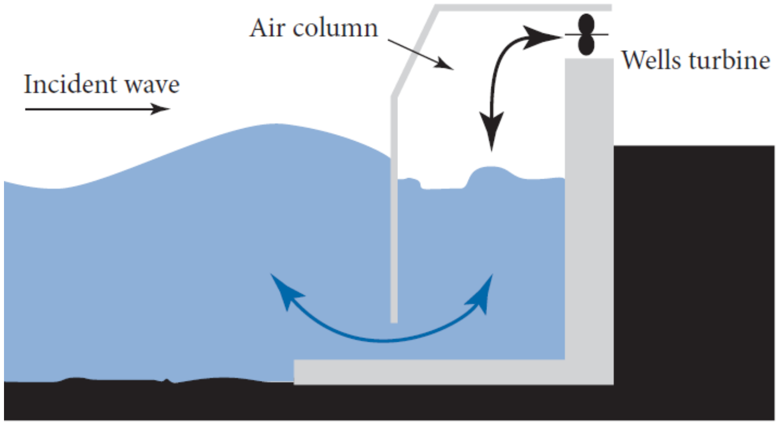
Shore-based device: Oscillating Water Column

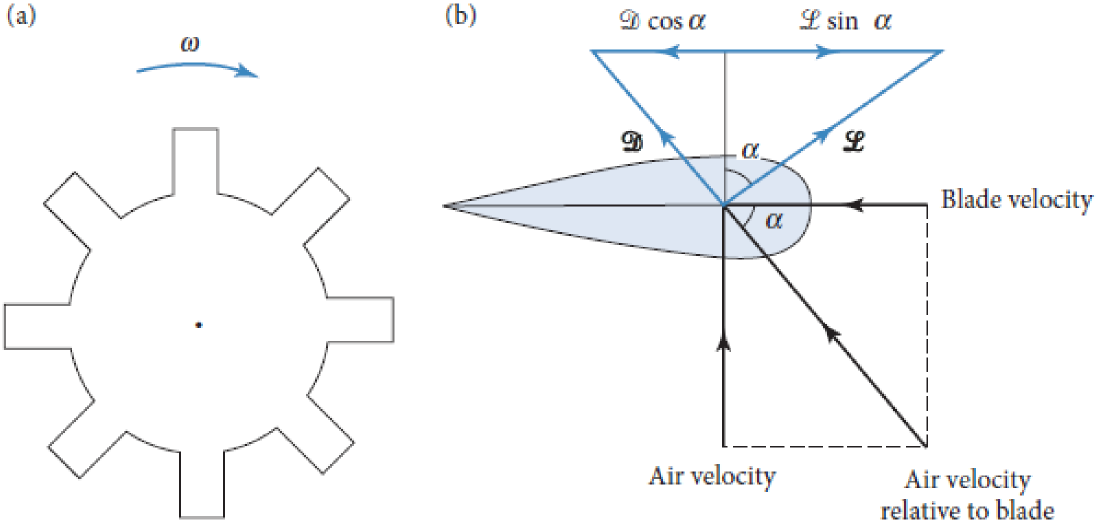
The **Oscillating Water Column** (OWC) is a shore-based device in which the moving parts are in air, not water. Air oscillates in a chamber and drives a **Wells turbine**, which spins in one direction.

The turbine blades are symmetrical about the direction of their motion. Relative to any blade, the air flow is at a non-zero angle of attack, *α*. Net force on blade is given by

$$F = L\sin\alpha - D\cos\alpha$$

where L = lift force and D = drag force. Blade designed such that $D << L$.





Submerged Wavepower Devices

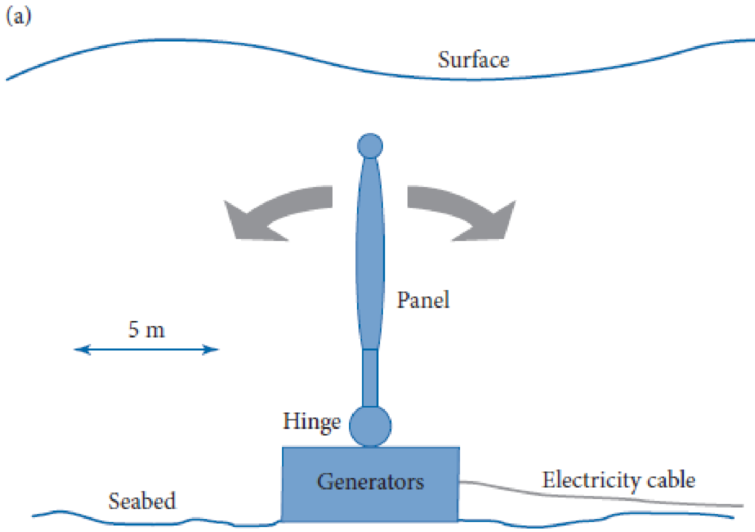
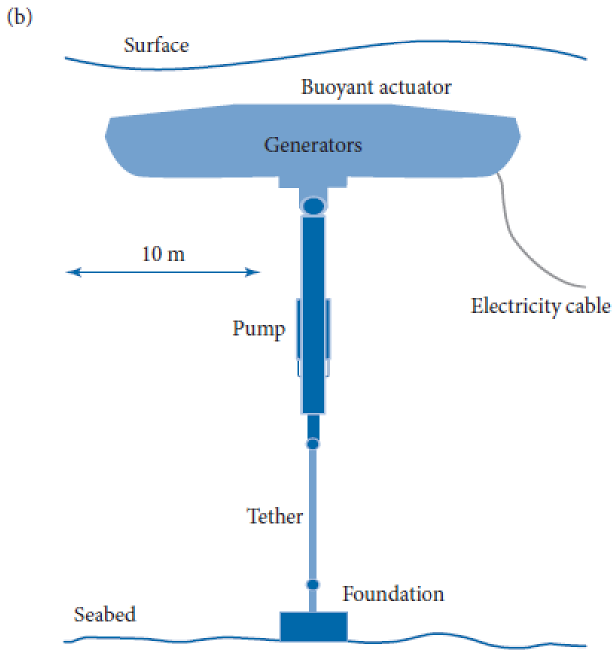


Fig. 6.25 (a) WaveRoller oscillating wave surge converter.

WaveRoller (Finland) operates in depths of 8-20 m, 0.3-2 km from shore.
Output = 0.5–1 MW. Capacity Factor = 25-50%.



Ceto6 (Australia) absorbs energy from any direction (point absorber), buoyancy chamber 1-2 m below surface. Output = 1 MW.

Environmental impact and potential of wave power

Environmental impact

Offshore devices lower visual impact than on-shore sites
No greenhouse gas emissions
Some impact on marine ecology

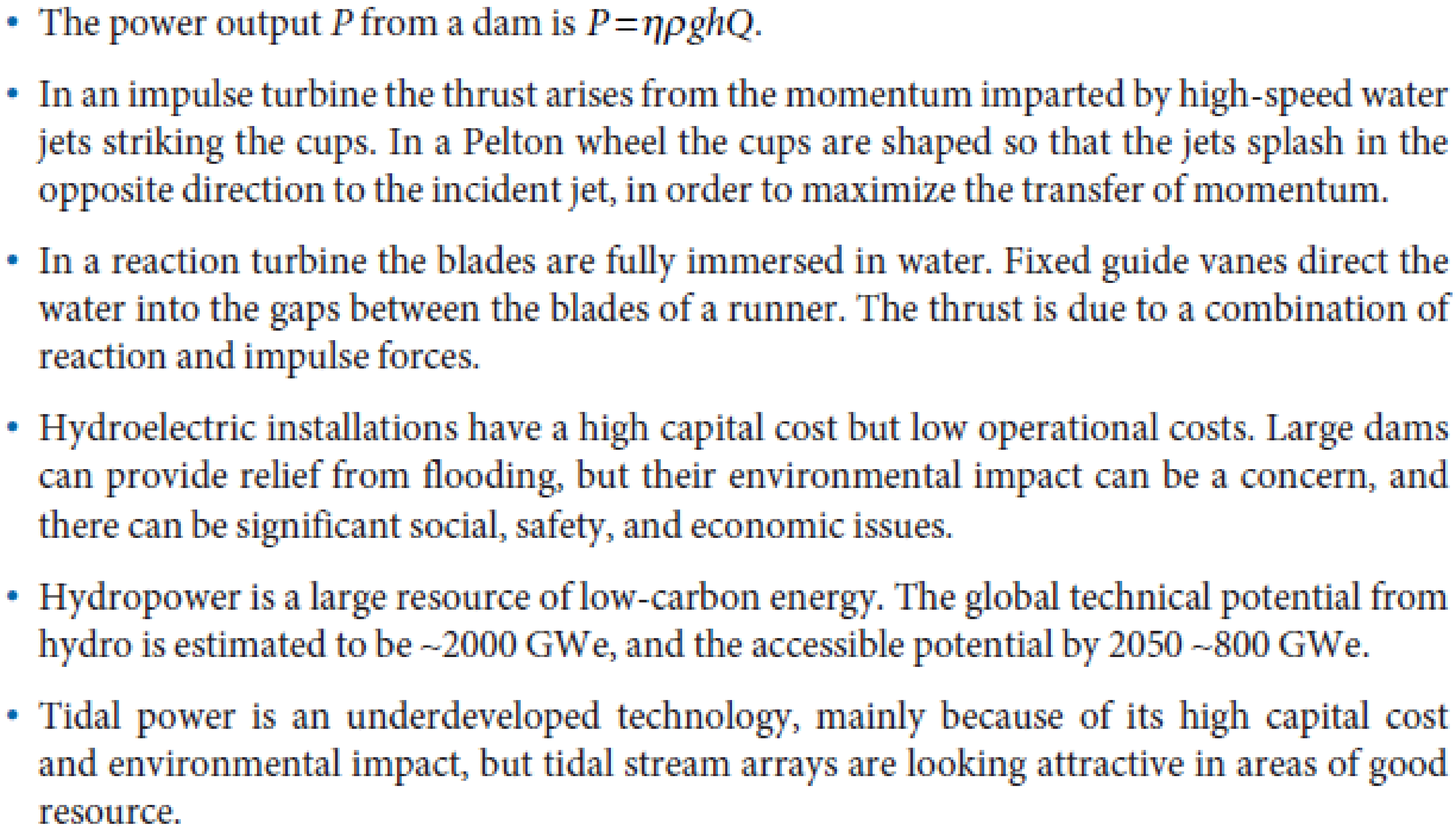
Size of resource

Global resource = 2 TW (Europe 240 GW, Australia 280 GW, USA 220 GW, Africa 320 GW, Asia 320 GW

Potential

Regarded as high risk technology, expensive and not currently competitive with wind or solar power
Accessible potential = 50 GWe
No major development likely until dependence on fossil fuels reduces significantly

Key Points



- The power output P from a dam is $P = \eta\rho g h Q$.
- In an impulse turbine the thrust arises from the momentum imparted by high-speed water jets striking the cups. In a Pelton wheel the cups are shaped so that the jets splash in the opposite direction to the incident jet, in order to maximize the transfer of momentum.
- In a reaction turbine the blades are fully immersed in water. Fixed guide vanes direct the water into the gaps between the blades of a runner. The thrust is due to a combination of reaction and impulse forces.
- Hydroelectric installations have a high capital cost but low operational costs. Large dams can provide relief from flooding, but their environmental impact can be a concern, and there can be significant social, safety, and economic issues.
- Hydropower is a large resource of low-carbon energy. The global technical potential from hydro is estimated to be ~2000 GWe, and the accessible potential by 2050 ~800 GWe.
- Tidal power is an underdeveloped technology, mainly because of its high capital cost and environmental impact, but tidal stream arrays are looking attractive in areas of good resource.

Key Points

- Approximate average power output of a tidal barrage operating on the ebb tide is $P_{\text{ave}} = \rho g A h^2/(4T)$, where h is the tidal range and T is the tidal period.
- The global tidal energy technical potential is ~2500 GWe with an economic potential of ~75 GWe from tidal barrages and ~100 GWe from tidal stream devices, with ~2–4 GWe around the UK. The accessible potential from tidal power by 2050 is estimated to be 50 GWe.
- Wave power is large natural resource with a global technical potential of ~2000 GW, with the WEC estimating ~200 GWe for the global economic potential. Significant issues need to be resolved, especially survivability in storms, and capital cost. The accessible potential from wave power by 2050 is estimated to be 50 GWe.
- The power per unit width of wave-front is $P = \frac{1}{4}\rho g a^2 \sqrt{g\lambda/(2\pi)}$. In mid-ocean conditions the typical power per metre width of wave-front is 30–70 kW m^{-1}.
- Some shore-based wave power schemes (such as TAPCHAN and OWC) have been shown to be feasible for small-scale operation.
- Large-scale submerged devices (e.g. Seabased, WaveRoller, and CET0 6) can generate much more power and are starting commercial deployment.