Lecture 15 – Ocean Energy: Waves & Tides

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Outline

- History of Wave Energy
- Physical Principles and Wave Velocity
- Wave Energy Converters and Power Take-off (PTO) Systems
- Environmental Impact and Economics
- Tidal Energy

- B3: Chap 7 & 9
- B1: Sec 8.3-8.4

Wave Energy

Current Status of Ocean Energy

- Ocean energy remains a largely untapped renewable energy source, despite decades of development efforts.

- Deep water wave power resources are truly enormous, between 1–10 TW. The useful worldwide resource has been estimated to be greater than 2 TW.

- Approximately 529 MW of operating capacity at the end of 2017, >90% was represented by two tidal barrage facilities.

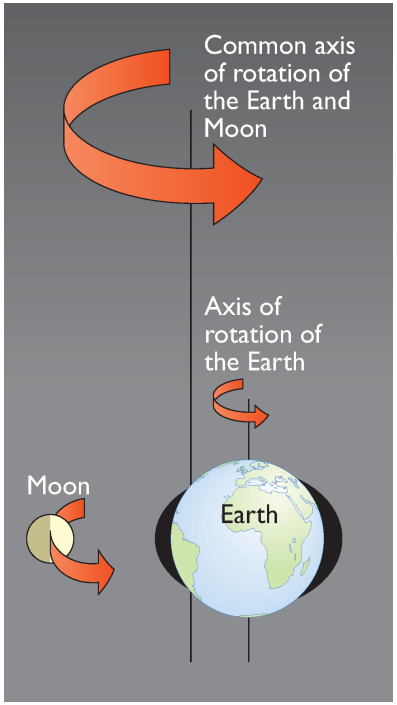
- Ocean energy technologies deployed in open waters (excluding tidal barrage) had a good year in 2017. Both tidal stream and wave energy deployments saw new capacity come online, much of it launched in the waters of Scotland.

- The year of 2017 ended with net capacity additions: 17 MW of tidal stream and 8 MW of wave energy capacity.

Tide vis-à-vis Wave

Key difference between **wave** & **tide**?

- **Tides** are formed because of the interaction of the gravitational forces between the Earth, the moon, and the sun. The moon itself has a more prominent effect on the tides, as it is much closer to the Earth. The tides at shorelines of oceans will rise and fall about twice a day.



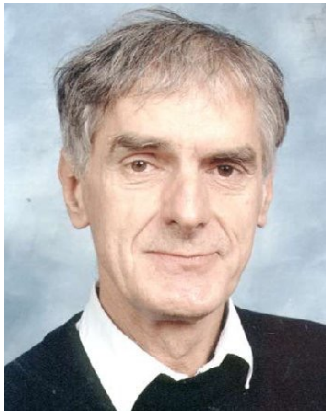
- **Waves** are formed because of the gusting or raging force exerted by the wind on the water surface. Wave energy uses the kinetic force of waves to produce energy

History of Wave Power

- The first known patent using energy from ocean waves dates back to 1799, and was filed in Paris by Girard & his son.
- An early application of wave power was a device constructed around 1910 by Bochaux-Praceique to light and power his house in France.

Yoshio Masuda

- Modern scientific pursuit was pioneered by Yoshio Masuda's experiments in 1940s.
- A renewed interest in wave energy was motivated by the oil crisis in 1973 (notably Stephen Salter from the U of Edinburgh)



Stephen Salter

Masuda’s Navigation Buoy

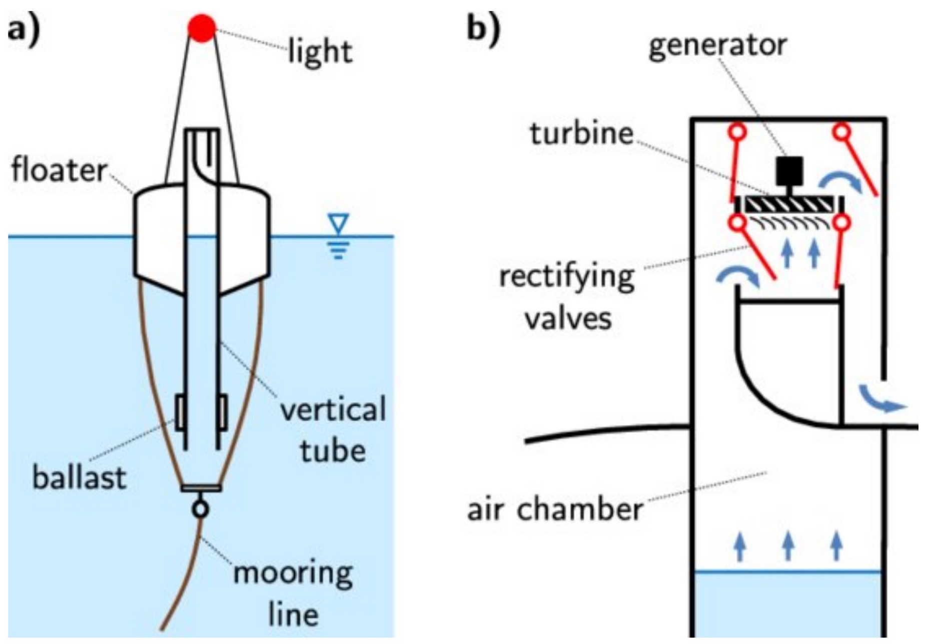
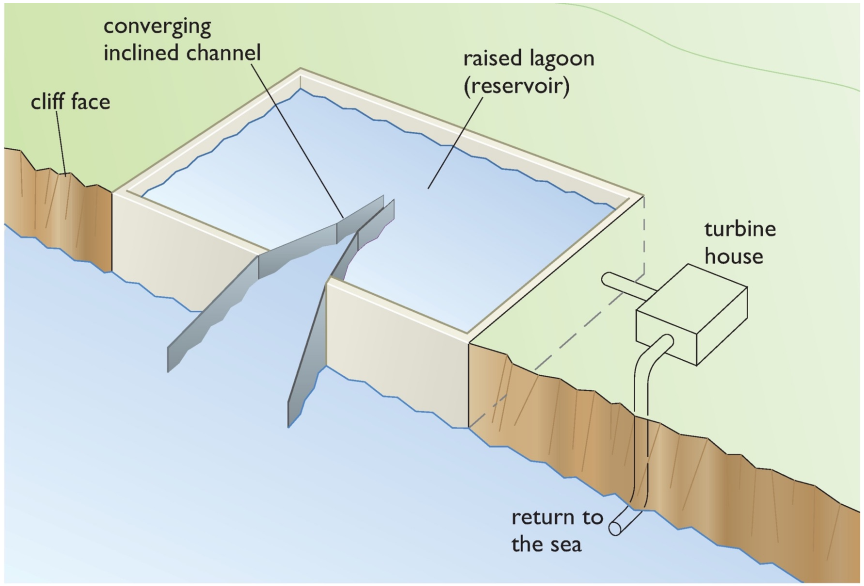


Fig: a) Yoshio Masuda’s navigation buoy based on the OWC (oscillating water columns) principle. b) Detail of the turbine and the rectifying valves of the PTO system under exhalation conditions.

- The device is a floater rigidly pierced by a vertical tube.
- The above the water line upper part forms an air chamber open to the atmosphere through a duct where an air turbine is installed.
- Wave action alternately compresses/decompresses the trapped air which forces air to flow through the turbine

Introductory Case



(a)

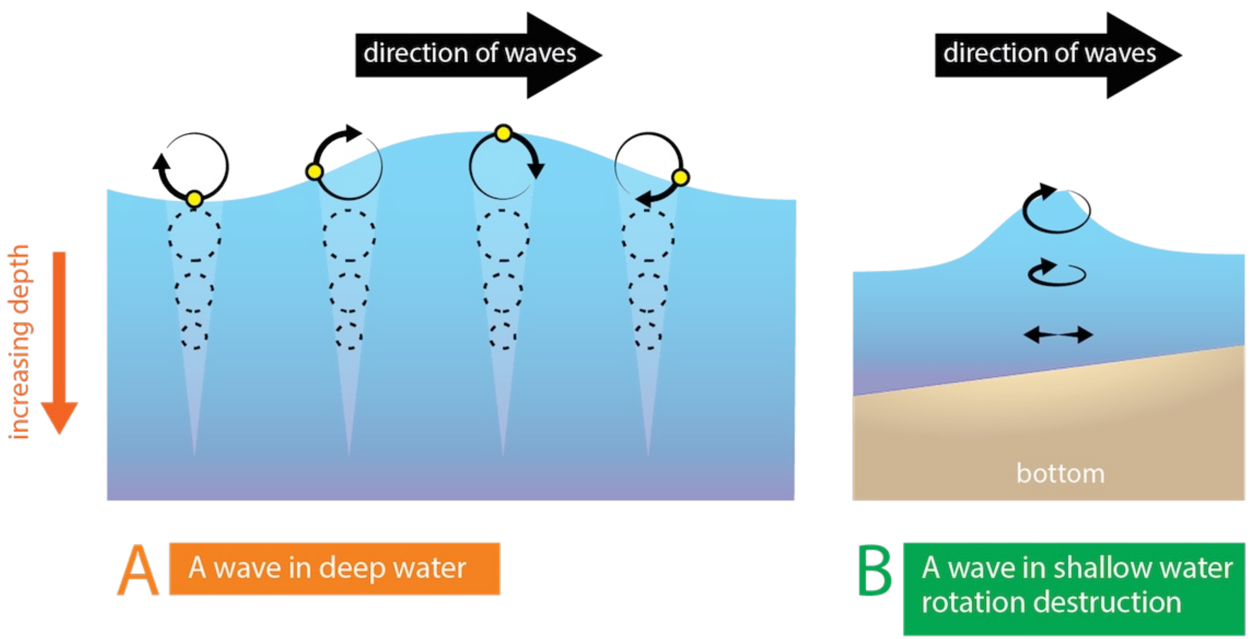

(b)

- A 350 kW prototype TAPCHAN wave energy converter built by Norwave in 1985 on a small Norwegian island.
- The channel walls 10m high and 170m long
- Kinetic energy in the waves → potential energy → electricity
- To be effective requiring a good wave climate:
  high & consistent waves +
  deep water close to the shore +
  small tidal range

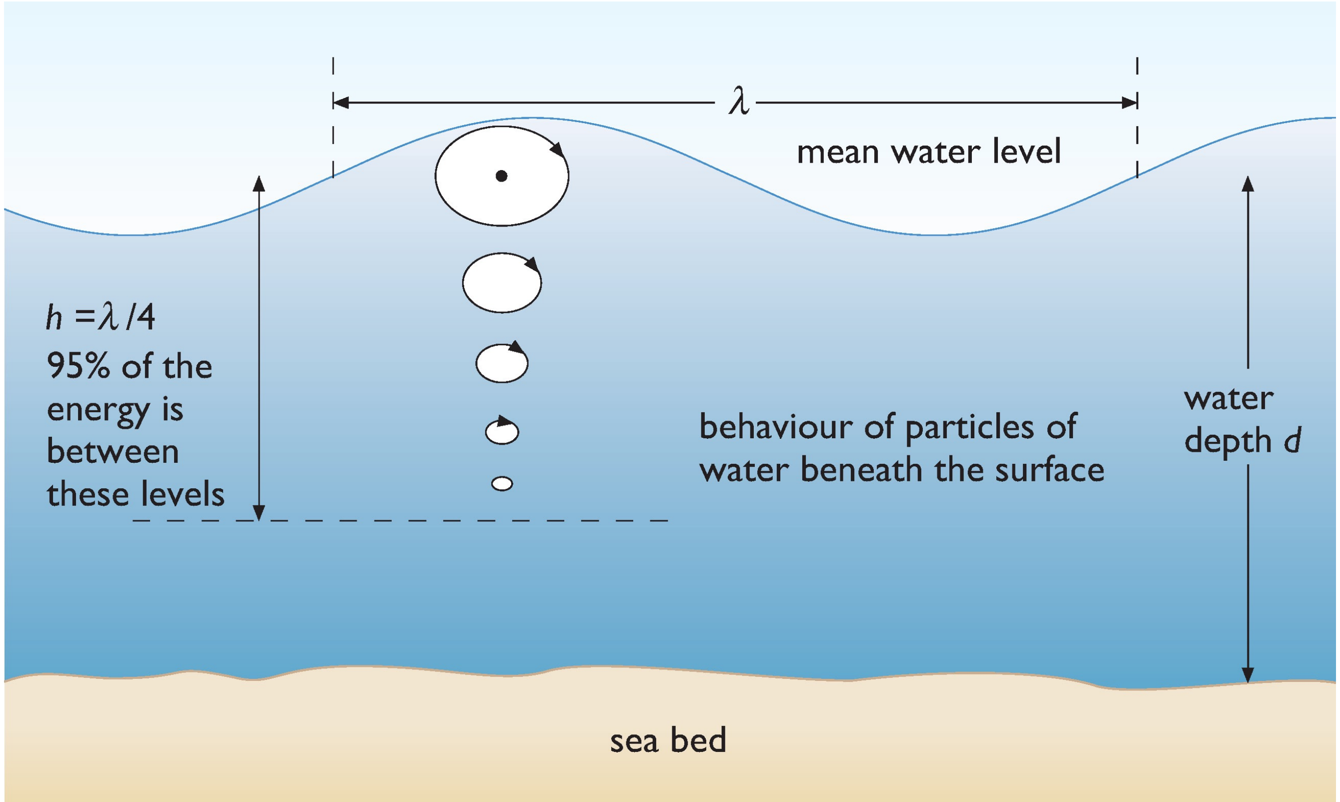
Physical Principles of Wave Energy

Ocean waves are generated by **wind** passing over long stretches of water known as ‘fetches’. Three main processes:

1. Air flowing over the sea exerts a tangential stress on the water surface, resulting in the formation and growth of waves
2. Turbulent air flow creates rapidly varying shear stresses & pressure fluctuations → further wave development
3. Wind can exert a stronger force on the upwind face of the wave, causing additional wave growth.



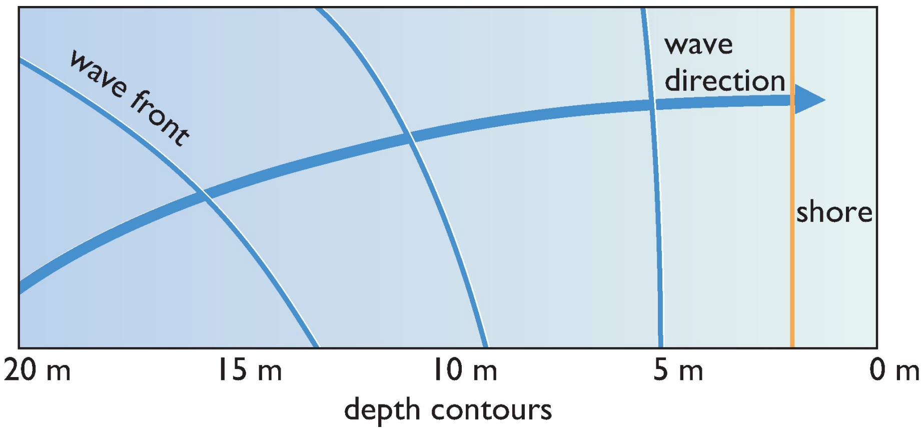
Beneath Surface



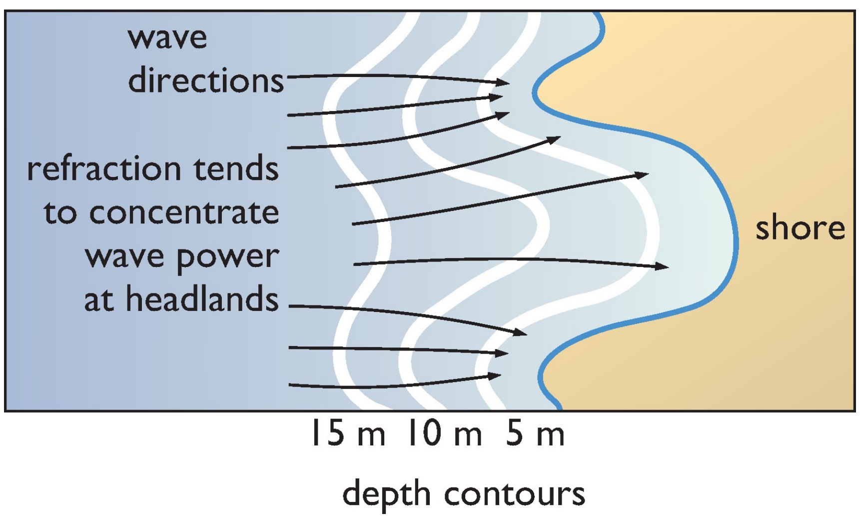
- Waves are composed of orbiting particles of water.
- Near the surface, orbits are the same size as the wave height.
- The size of orbits decreases exponentially with depth.

Refraction

Refraction: change of wave direction due to change of wave velocity

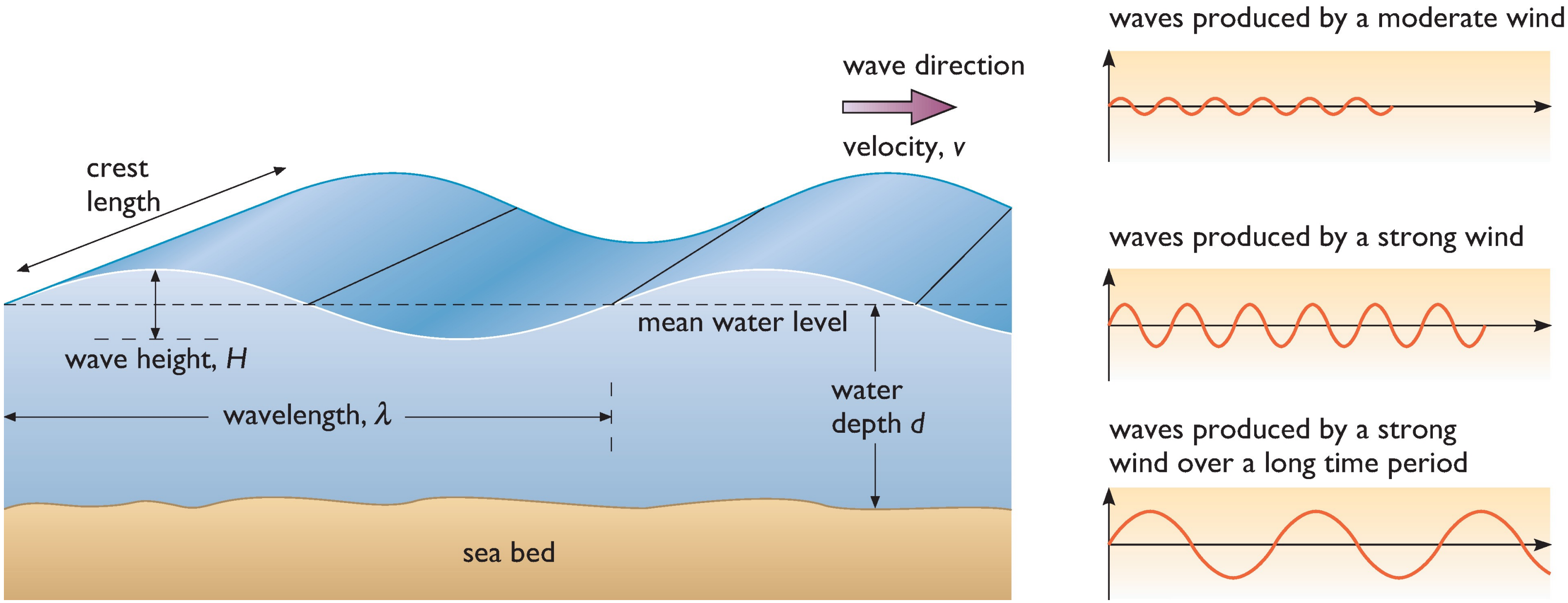


Water velocity reduces as waves travel from deep to shallow water



Concentration effects of refraction

Key Characteristics of Wave



The ‘regular’ wave is characterized by:

- **wavelength (λ)** – the distance between successive peaks
- **depth (d)** – the distance from mean water level to sea bed
- **height (H)** – the difference in height between peaks and valleys
- **period (T)** – the time in seconds taken for successive peaks to pass a given fixed point.

$$v = \lambda / T = \lambda f$$

Long waves travel faster than the shorter waves!

Wave Velocity

- Deep water waves $(d > \lambda/2)$: $v = \dfrac{gT}{2\pi}$
- Shallow water waves $(d < \lambda/4)$: $v = \sqrt{gd}$
- Intermediate water waves: $v = f(d, T)$

Frequency dispersion of gravity waves on the surface of deep water, shallow water and at intermediate depth, according to linear wave theory

quantity	symbol	units	deep water ($h > \frac{1}{2}\lambda$)	shallow water ($h < 0.05\,\lambda$)	intermediate depth (all λ and h)
dispersion relation	$\Omega(k)$	rad / s	$\sqrt{gk} = \sqrt{\frac{2\pi\, g}{\lambda}}$	$k\sqrt{gh} = \frac{2\pi}{\lambda}\sqrt{gh}$	$\sqrt{gk\,\tanh(kh)} = \sqrt{\frac{2\pi g}{\lambda}\tanh\left(\frac{2\pi h}{\lambda}\right)}$
phase velocity	$c_p = \frac{\lambda}{T} = \frac{\omega}{k}$	m / s	$\sqrt{\frac{g}{k}} = \frac{g}{\omega} = \frac{g}{2\pi}T$	$\sqrt{gh}$	$\sqrt{\frac{g}{k}\tanh(kh)}$
group velocity	$c_g = \frac{\partial\Omega}{\partial k}$	m / s	$\frac{1}{2}\sqrt{\frac{g}{k}} = \frac{1}{2}\frac{g}{\omega} = \frac{g}{4\pi}T$	$\sqrt{gh}$	$\frac{1}{2}c_p\left(1 + \frac{2kh}{\sinh(2kh)}\right)$
ratio	$\frac{c_g}{c_p}$	-	$\frac{1}{2}$	1	$\frac{1}{2}\left(1 + \frac{2kh}{\sinh(2kh)}\right)$
wavelength	λ	m	$\frac{g}{2\pi}T^2$	$T\sqrt{gh}$	for given period T, the solution of: $\left(\frac{2\pi}{T}\right)^2 = \frac{2\pi g}{\lambda}\tanh\left(\frac{2\pi h}{\lambda}\right)$

Wave Power

The power of an idealized sinusoidal wave:

$$P = \frac{\rho g^2 H^2 T}{32\pi} \approx H^2 T \text{ (W/m)}$$

For example, a series of sinusoidal, 3-m waves with a period of 8 s would have power equal to

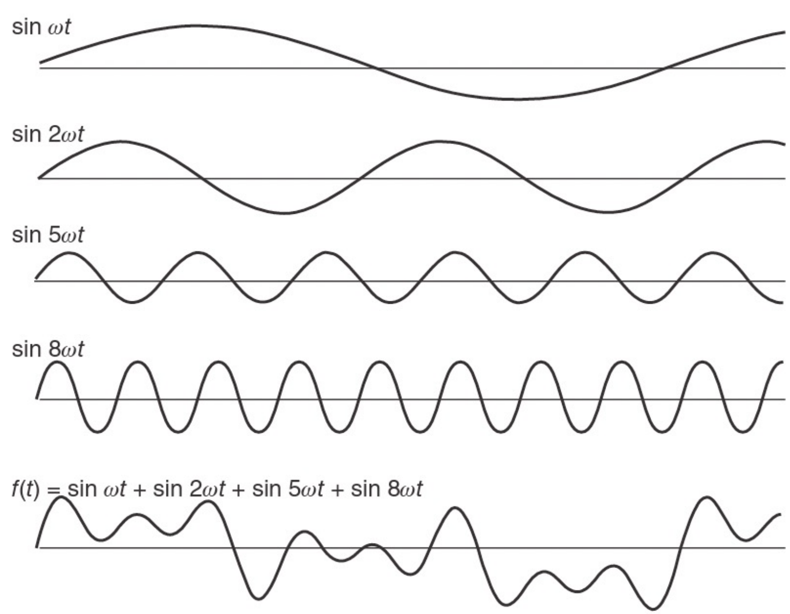
$$P = \frac{\rho g^2 H^2 T}{32\pi} = \frac{1}{32\pi} \cdot 1025 \frac{\text{kg}}{\text{m}^3} \cdot \left(\frac{9.8 \text{ m}}{\text{s}^2}\right)^2 \cdot (3 \text{ m})^2 \cdot 8 \text{ s}$$

$$= 70{,}500 \frac{\text{J/s}}{\text{m}} = 70.5 \text{ kW/m}$$

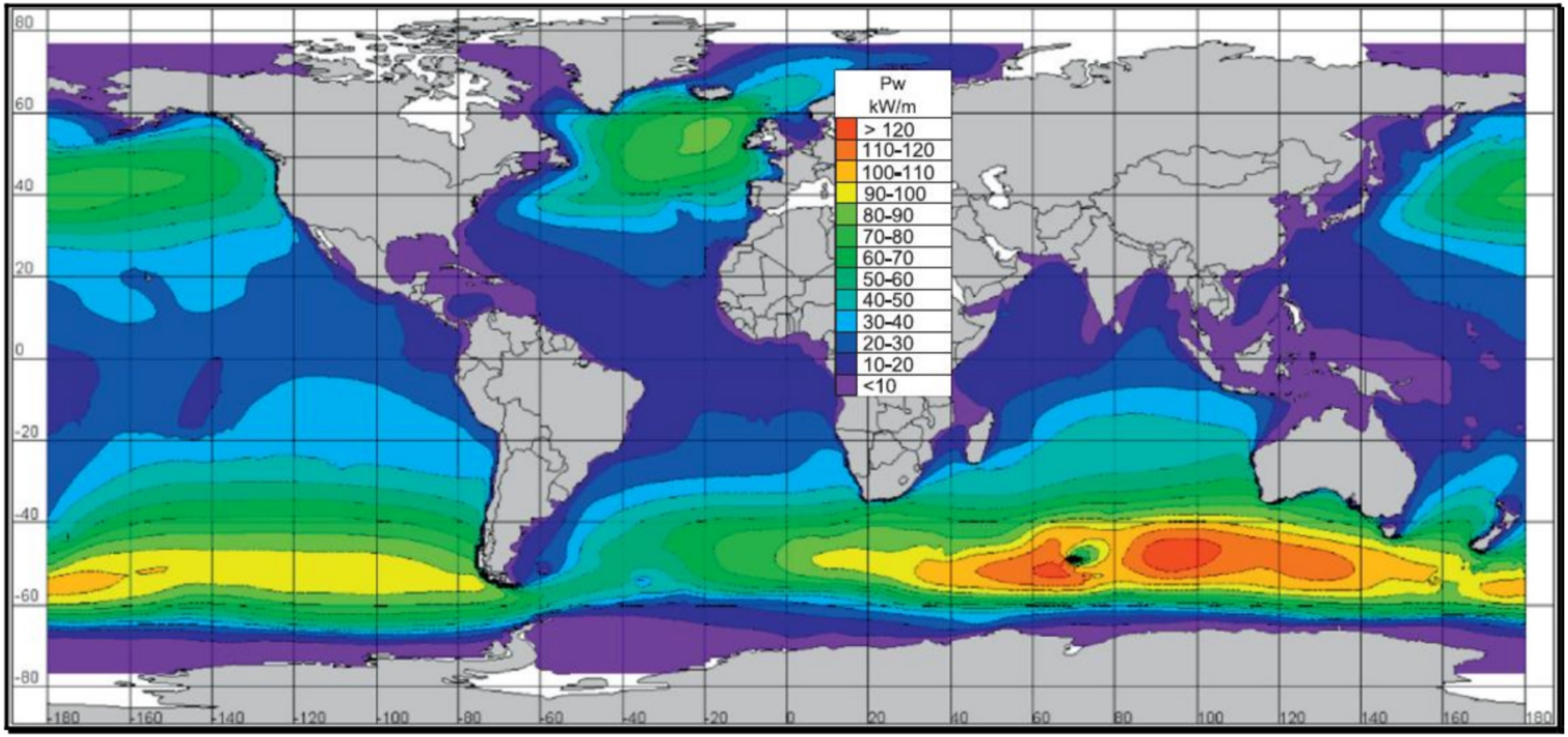
Actual ocean waves are a complex mix of waves having many different wavelengths.

$$P = 0.42\,(H_S)^2\,T_P$$

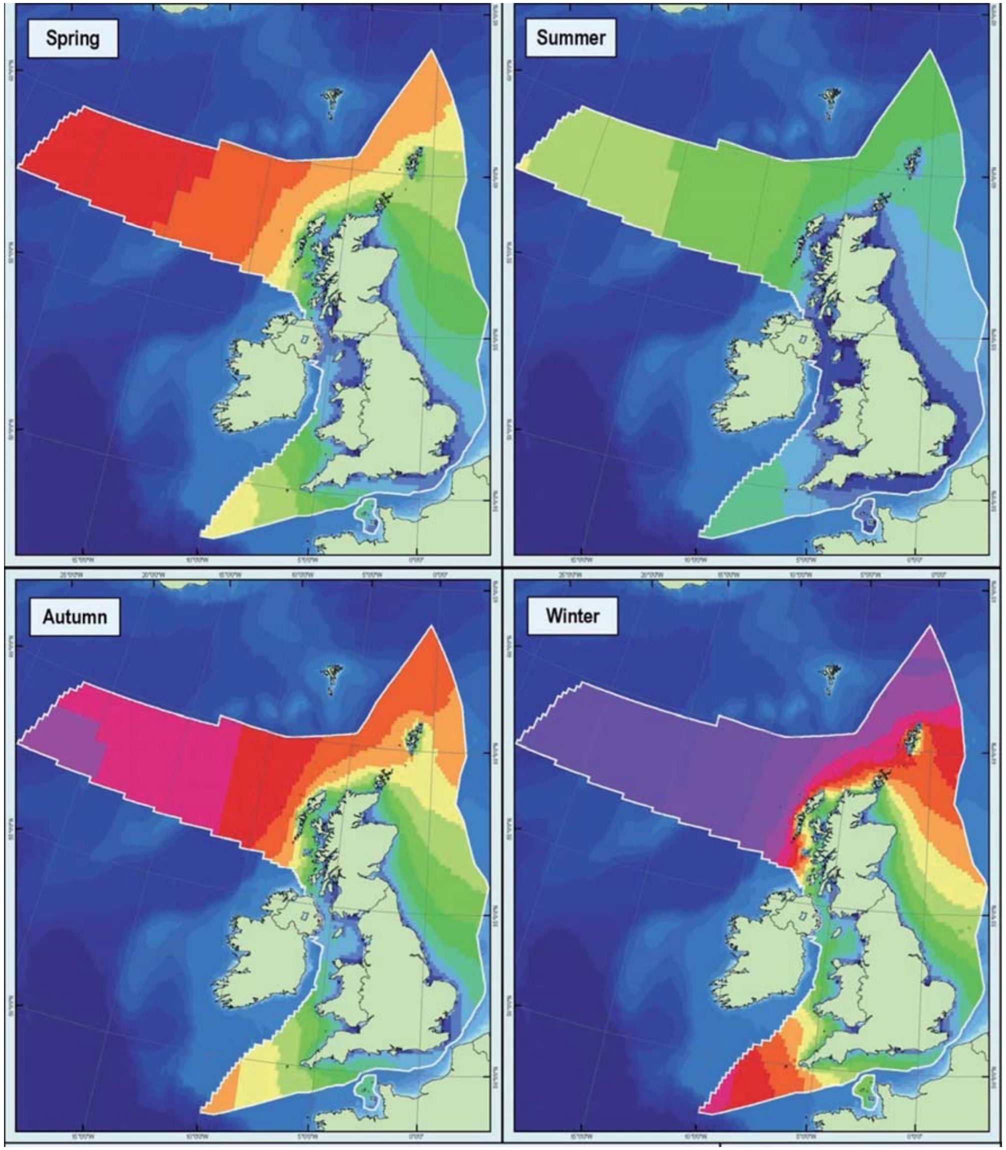
H_S: significant wave height (m);
T_P: peak wave period (s).

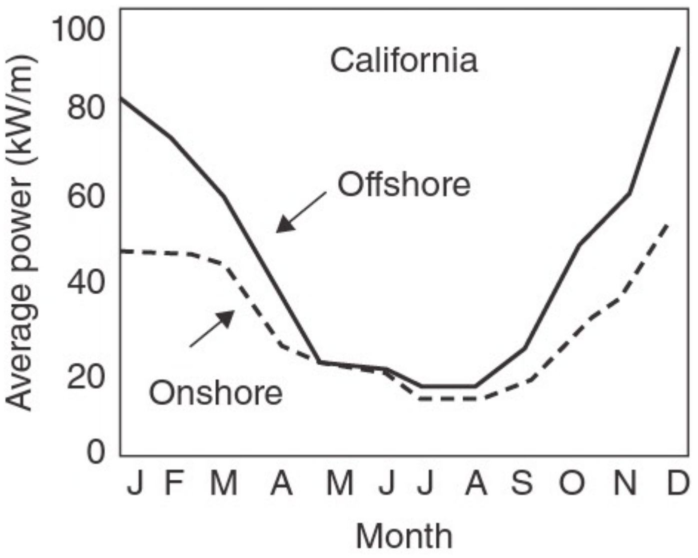


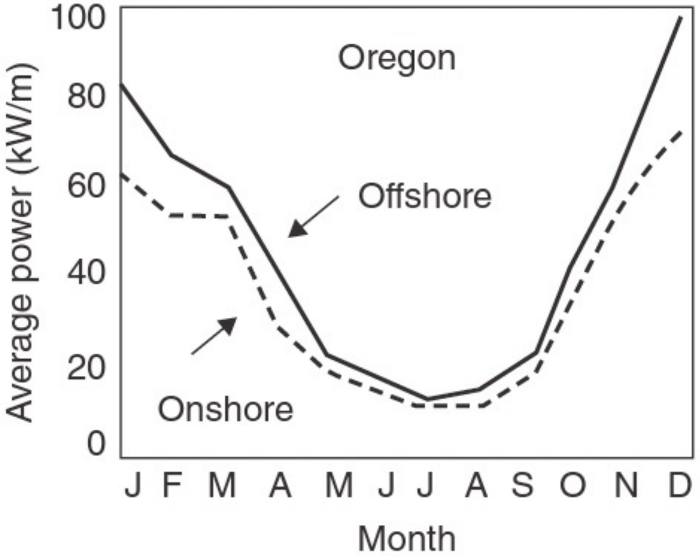
Global Annual Average Wave Power



Seasonal Variation in Wave Energy

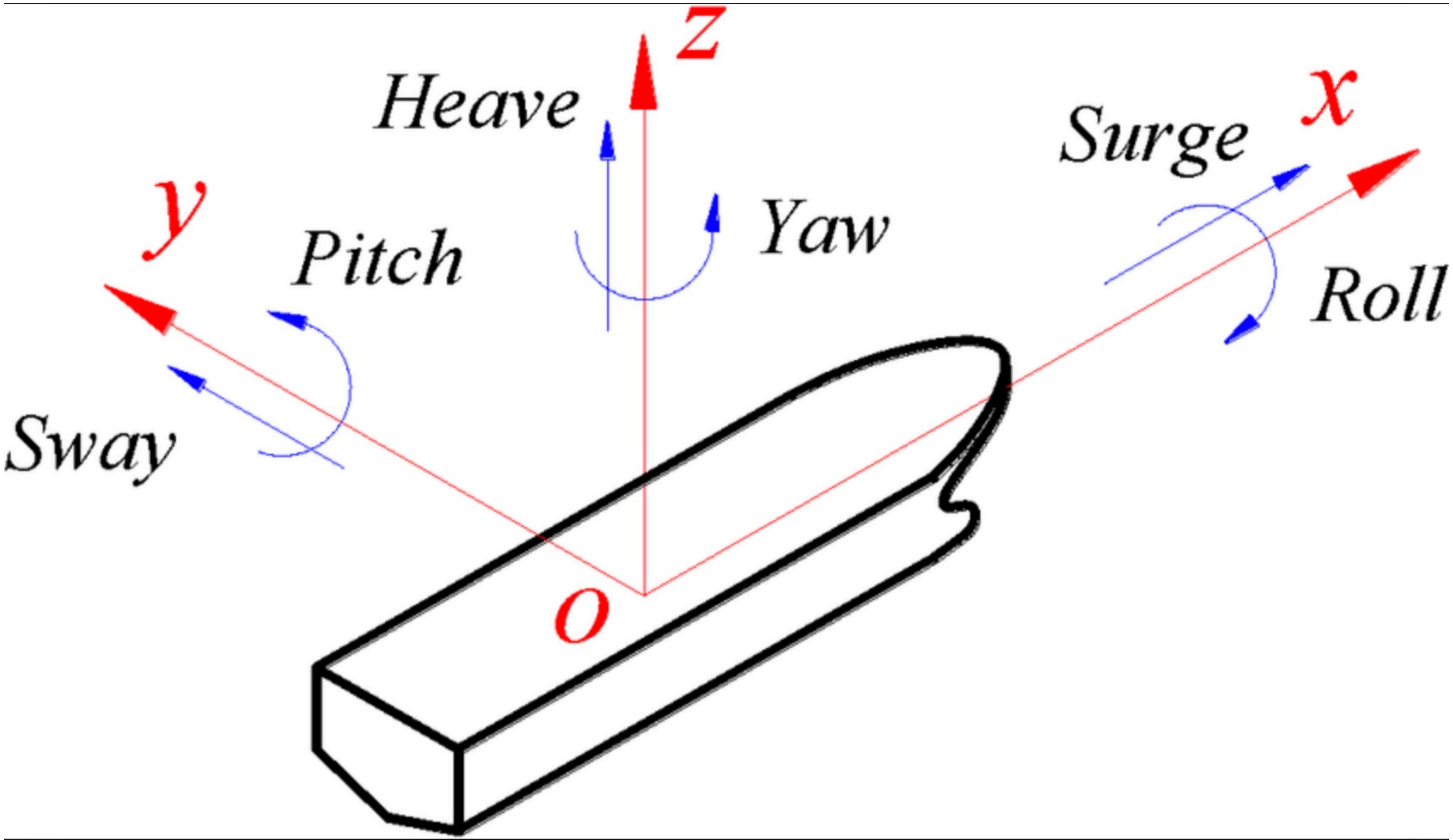






Types of Movement

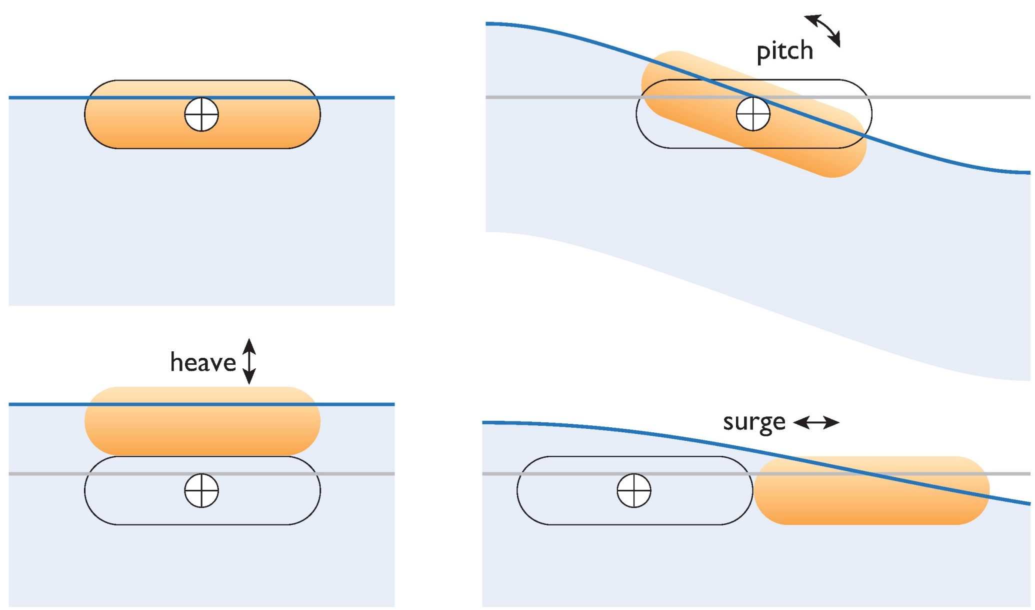
6 types of movement:



Types of Movement (Cont'd)

Sway, *roll* and *yaw*, not generally harnessed in wave energy conversion. The other three harnessed to varying degrees:

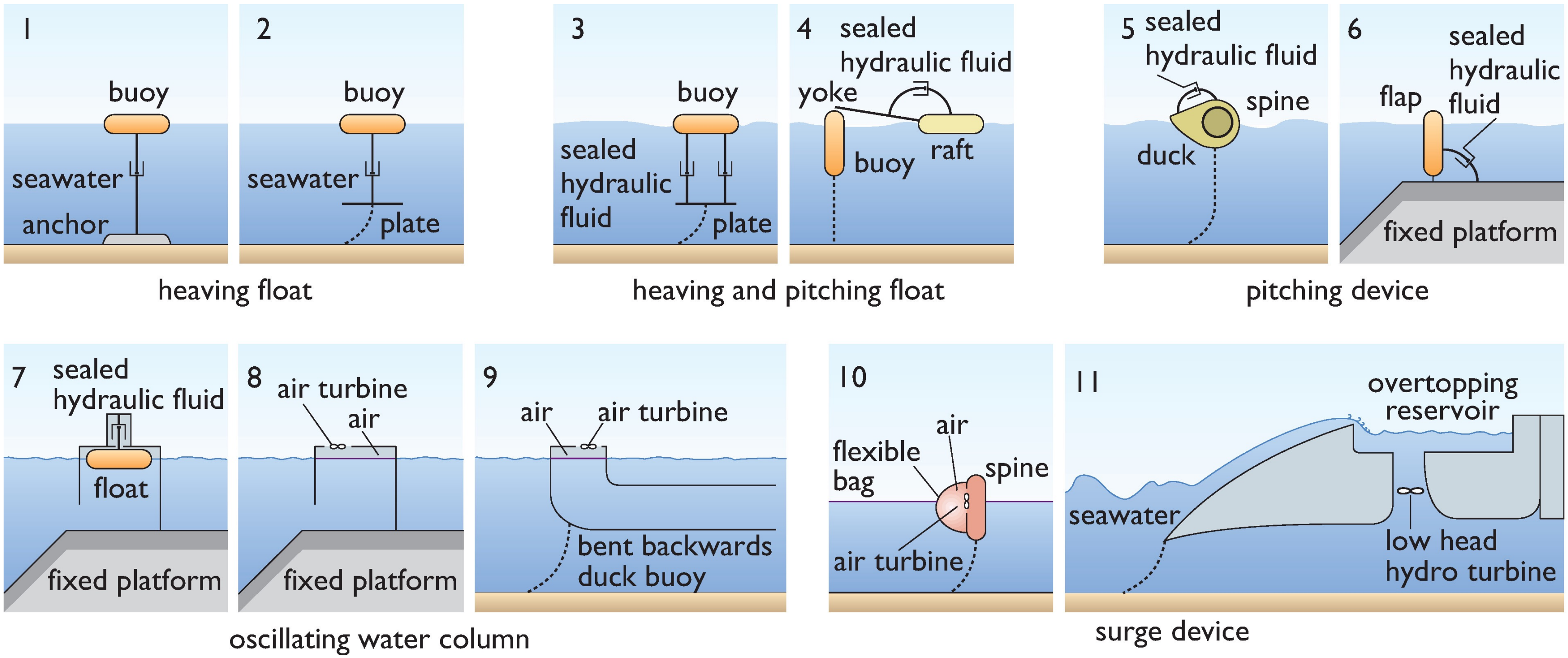
1. Pitch – waves cause the device, or part of it, to rotate about its axis.
2. Heave – waves cause the device to rise and fall vertically, though these devices have too high a natural frequency to be particularly effective.
3. Surge – waves cause the device to move horizontally backwards and forwards, Theoretically, surging motions are twice as energetic as heaving ones, making it preferable to harness this component of waves.



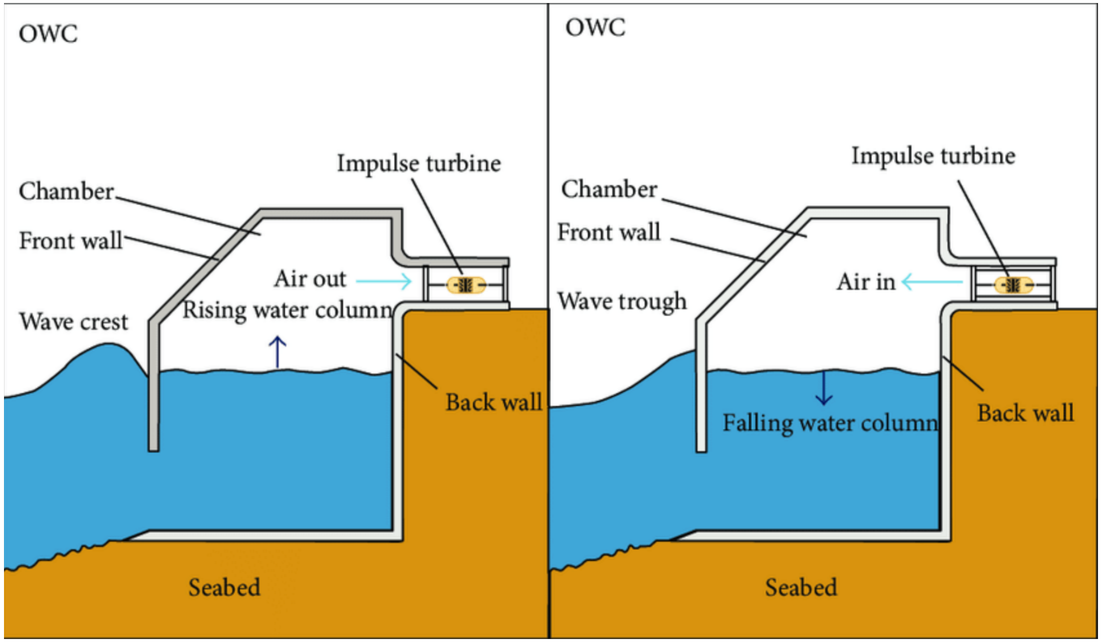
Configurations of Converters

Classified by
- Mode of operation
- Device location
- Geometry & orientation

Mode of Operation

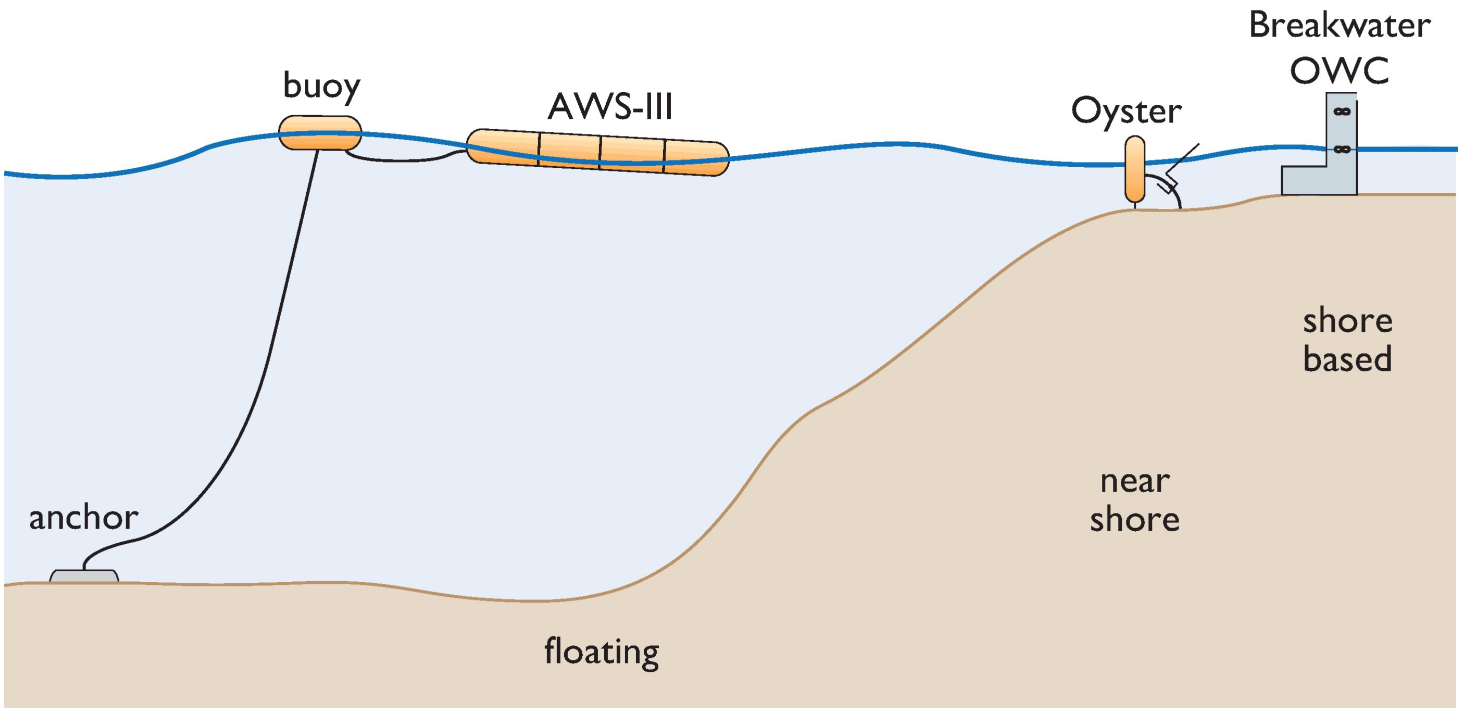


Oscillating Water Column (OWC)



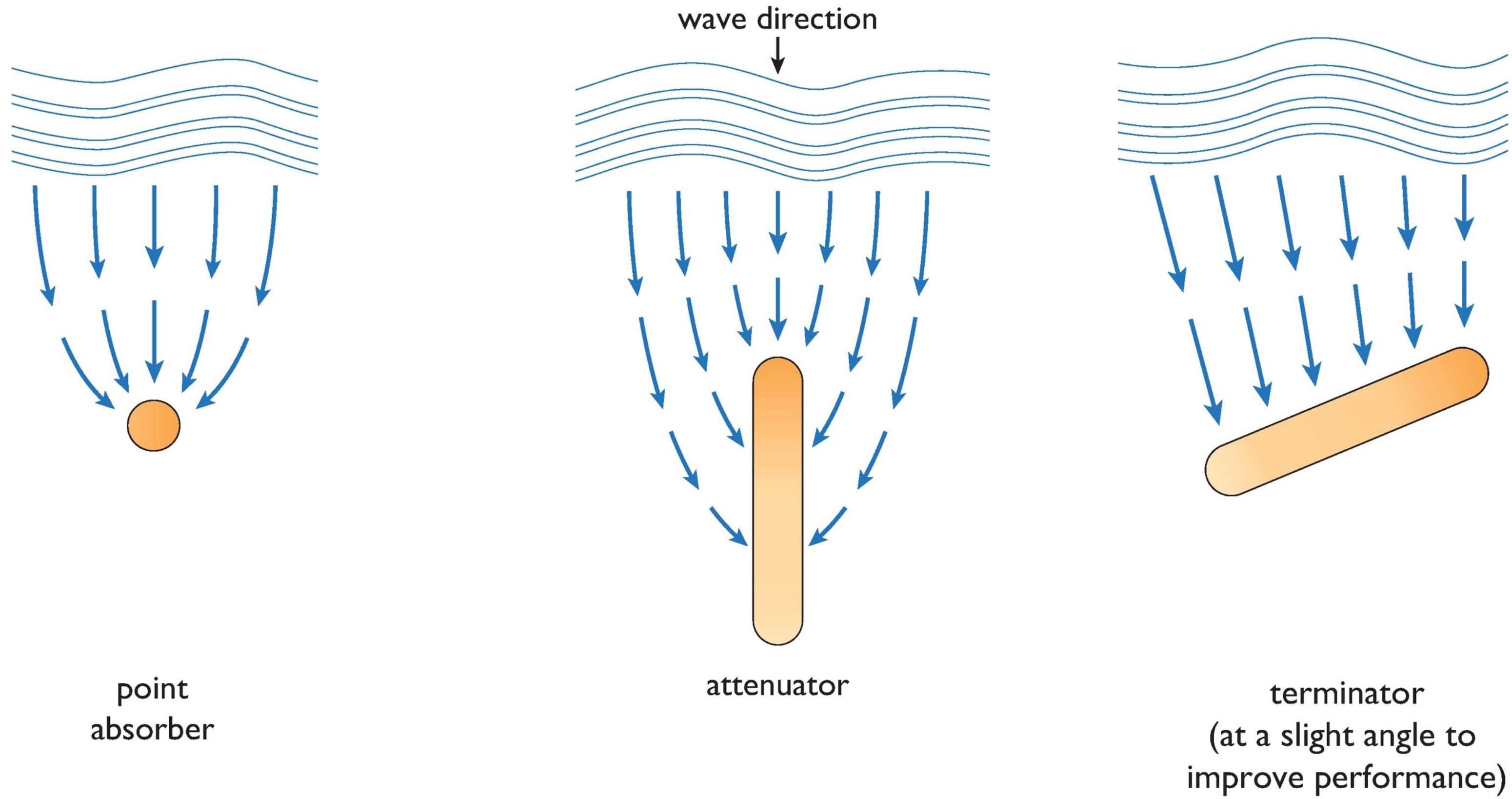
- An OWC uses a large volume of moving water as a piston in a cylinder.
- Air is forced out of the column as a wave rises and is drawn in as the wave falls.
- This movement of air turns a weir turbine at the top of the column.

Device Location



- fixed to the seabed, generally in shallow water (e.g. TAPCHAN)
- tie up in intermediate depths (e.g. Oyster)
- floating offshore in deep water (e.g. AWS-III).

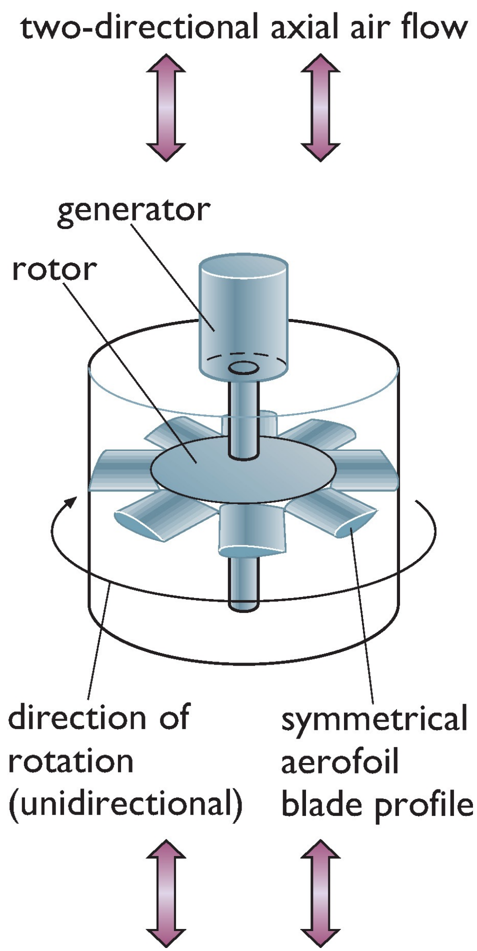
Geometry & Orientation

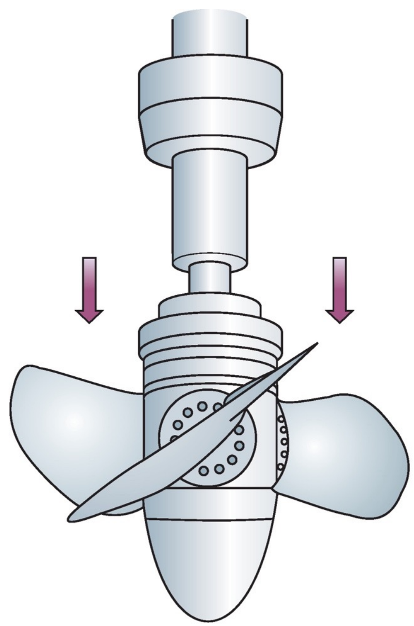


- Small dimensions, work by drawing wave energy from the water beyond their physical dimensions
- Principal axis perpendicular to the wave front
- Principal axis almost parallel to the incident wave front

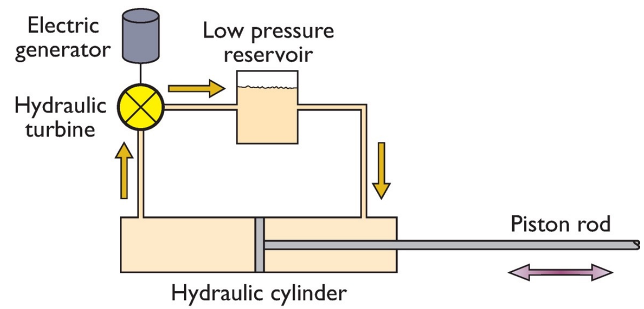
Power Take-off (PTO) Systems

- Covert primary motions of waves into linear/rotary motions for an electricity generator

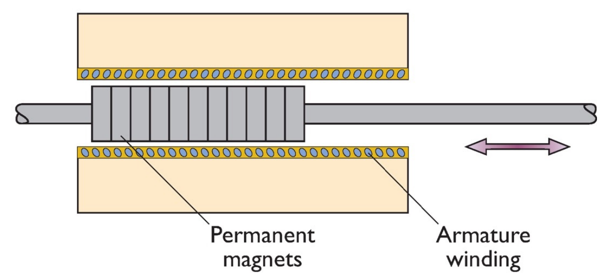




Kaplan turbine



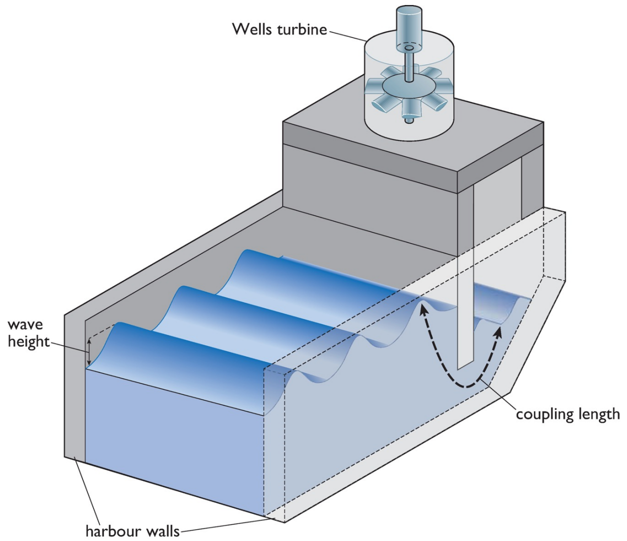
Hydraulic PTO



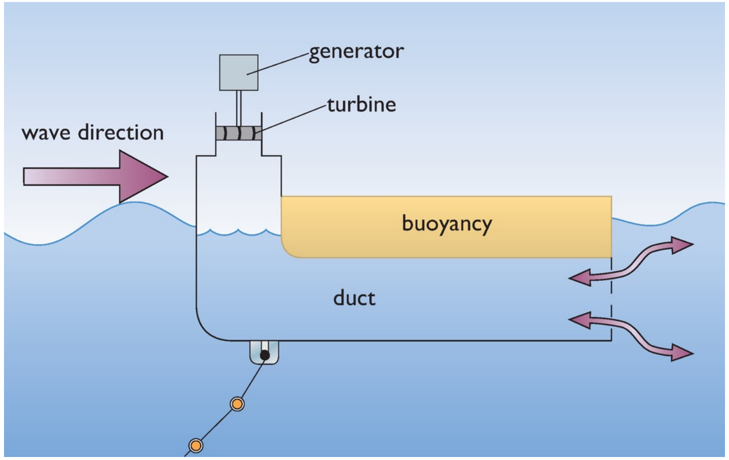
Linear generator PTO

Fixed vs Over-floating Devices

Resonant oscillating water column (OWC)



Backward bent duct buoy (BBDB)



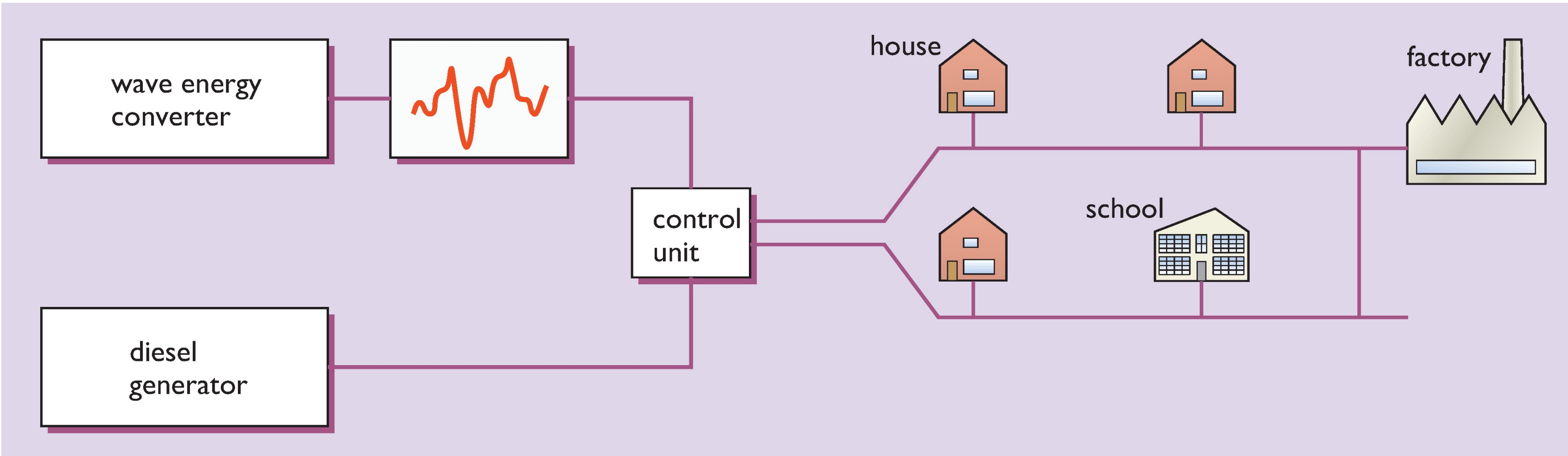
Fixed vs Over-floating Devices (Cont'd)

Q: What advantages and disadvantages of fixed/shore mounted devices over floating ones?

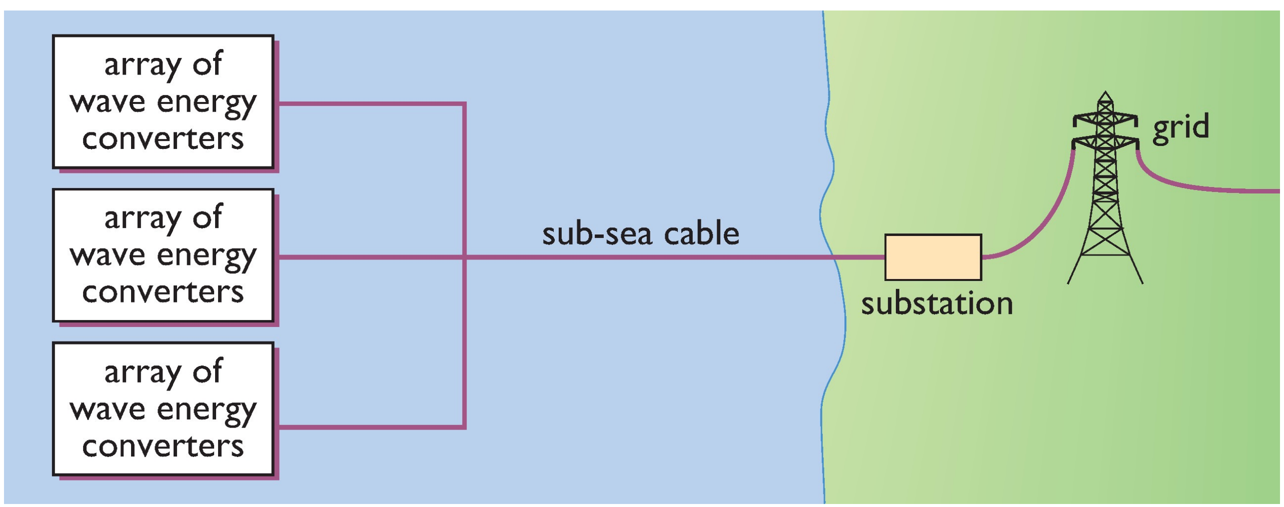
Pros	Cons
Have a fixed frame of reference; closer to a grid	Generally operate in shallow water and hence at lower wave power levels
Good access for maintenance purposes	Geographical location – only a limited number of sites are suitable for deployment
The seabed attenuates storm waves that could otherwise destroy the device and turbine	To optimize output, they need to be positioned in an area of small *tidal* range

Grid Integration

- For local communities



- For large power grids



A Future for Wave Energy

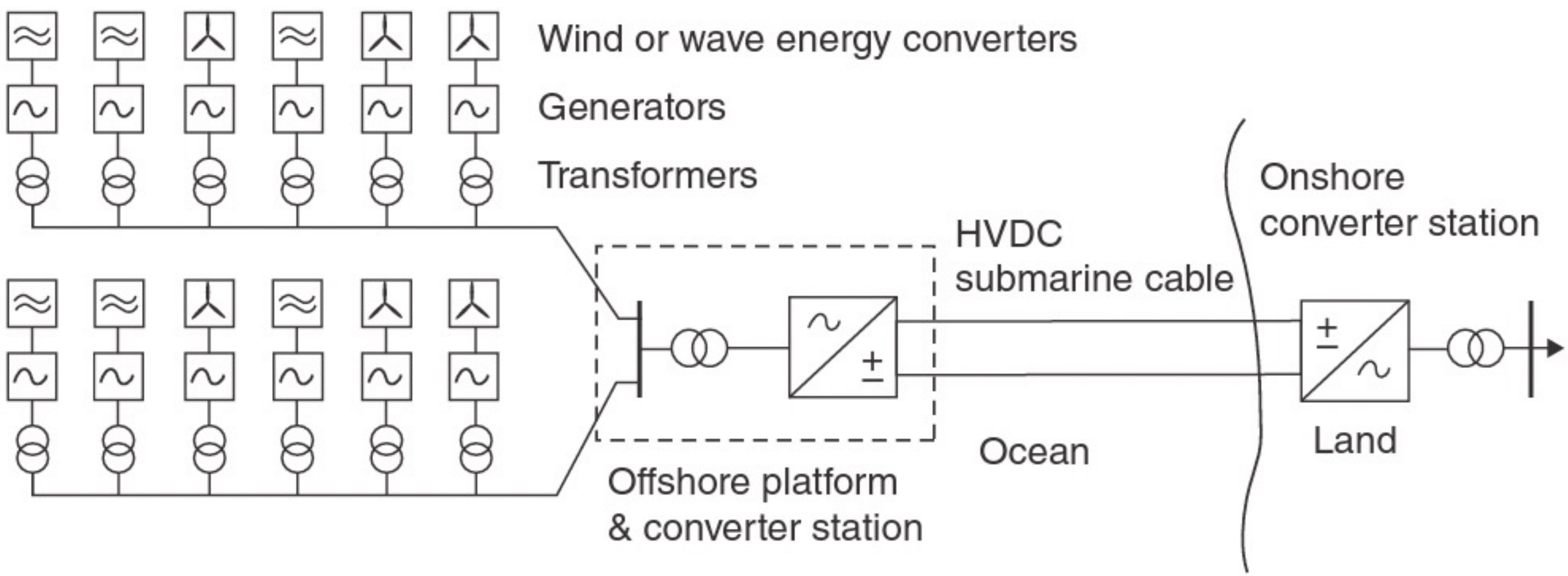
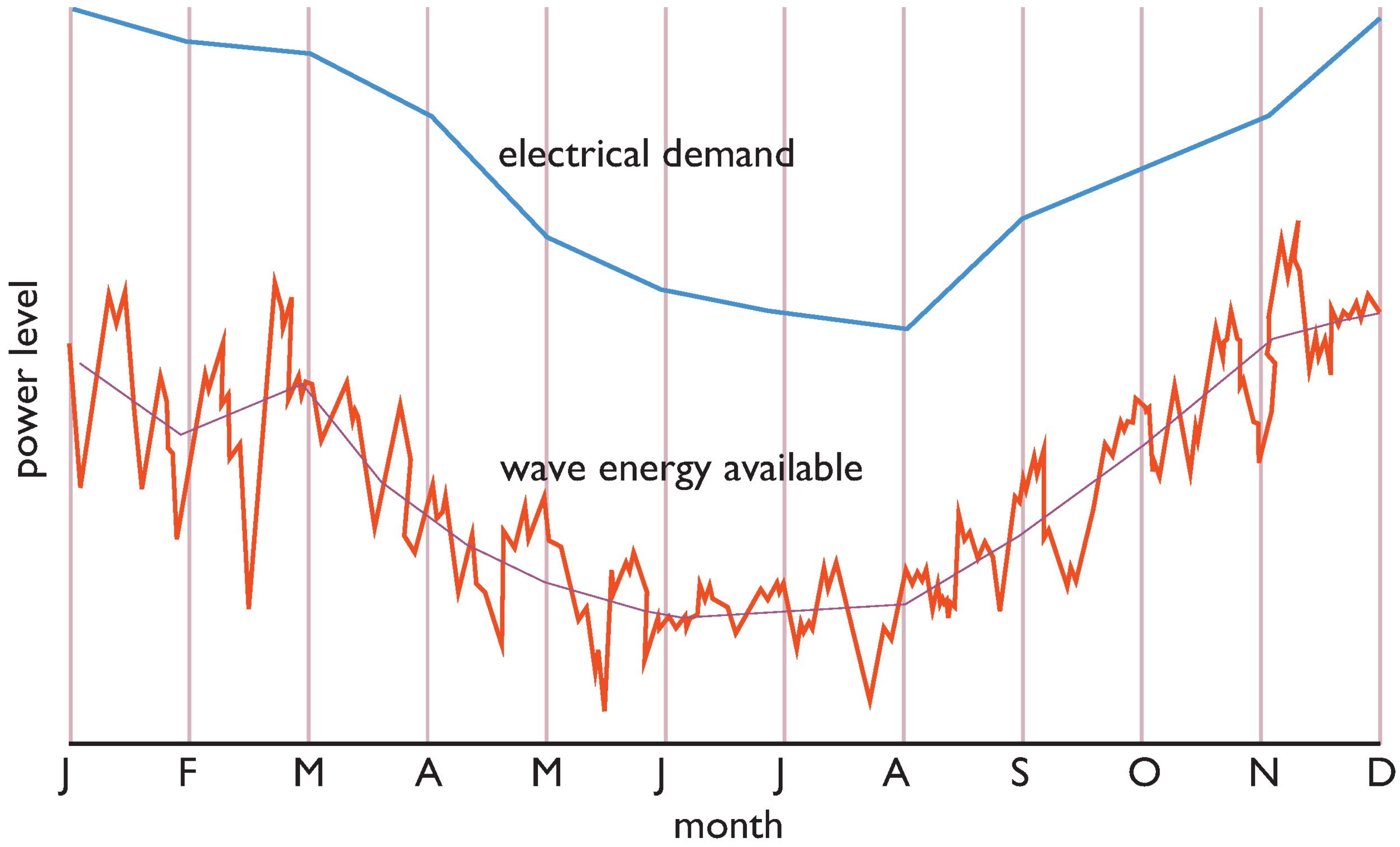


FIGURE 8.21 Colocated offshore wind and wave converters could share transmission costs. Redrawn from Stoutenburg and Jacobson (2011).

Grid Integration (Cont'd)

Fig: Seasonal availability of wave energy and demand in UK



More wave energy units → smoother power level

Wave Energy Economics

	Wave energy station	Conventional station
Capital Cost	High	Low
Capacity Factor (CF)	Low	High

- Low CF (15%) the cost of electricity would be 29.1p kW/h
- High CF (22%) the cost of electricity would be 19.9p kW/h

The capital cost is around £3,000–4,500 per installed kW.
The cost of particular schemes may vary markedly from this.

Wave energy costs can only be competitive if the running costs are significantly below those for a conventional station.

Environmental Impact

- Little potential for chemical pollution. At most, they may contain some lubricating or hydraulic oil, which will be carefully sealed
- Little visual impact, except where shore-mounted.
- Noise generation is likely to be low – generally lower than the noise of crashing waves
- Present a small (though not insignificant) hazard to shipping.
- They should present no difficulties to migrating fish.
- Floating schemes are incapable of extracting more than a small fraction of the energy of storms so will not significantly influence the coastal environment.
- It is estimated that near-shore wave energy schemes will release very small amount of CO_2, SO_2 and NO_x

Summary

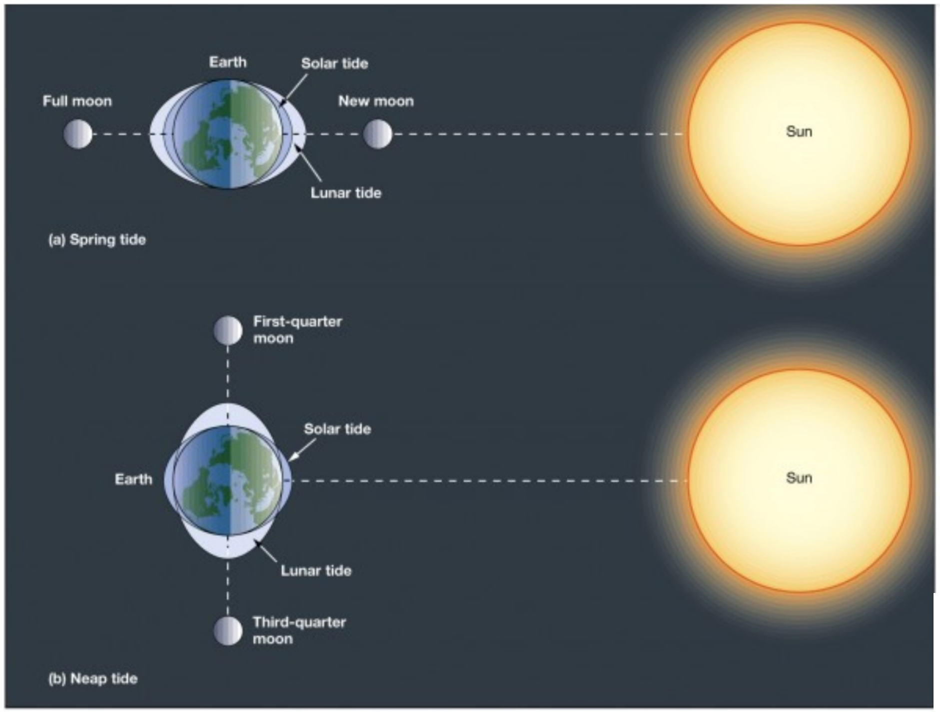
- Described the physical principles of wave energy
- Looked at the various wave energy resources available
- Introduced different wave energy technologies
- Studied wave energy economics
- Discussed the environmental impact of wave energy
- Examined the potential for grid integration of wave energy

Ocean Energy - Wave Power Station

Tidal Energy

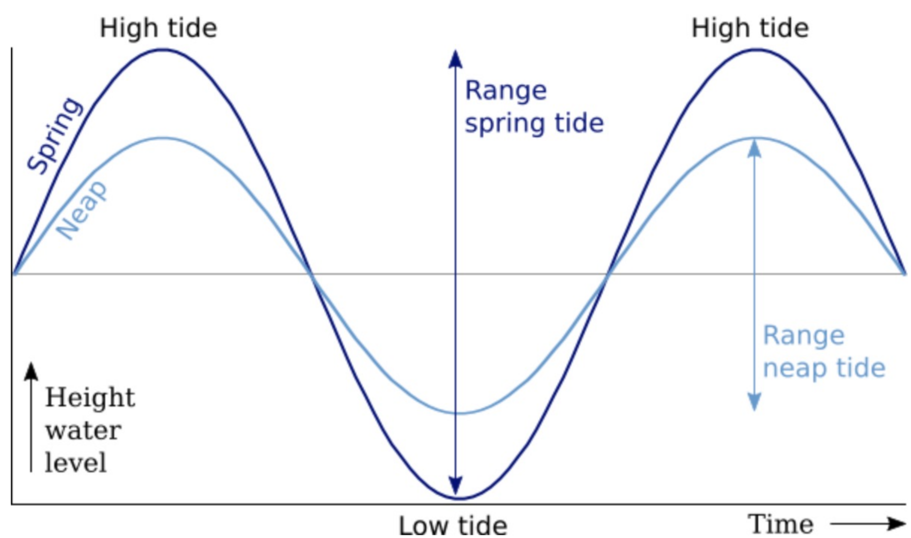
Origin of the Tides

Tidal changes are due to gravitational forces exerted mostly by the moon, and partially by the sun.



- Spring tides occur twice each lunar month all year long without regard to the season.
- Neap tides, which also occur twice a month, happen when the sun and moon are at right angles to each other.

Spring tide and neap tide levels are about 20% higher or lower than average.



Origin of the Tides (cont'd)

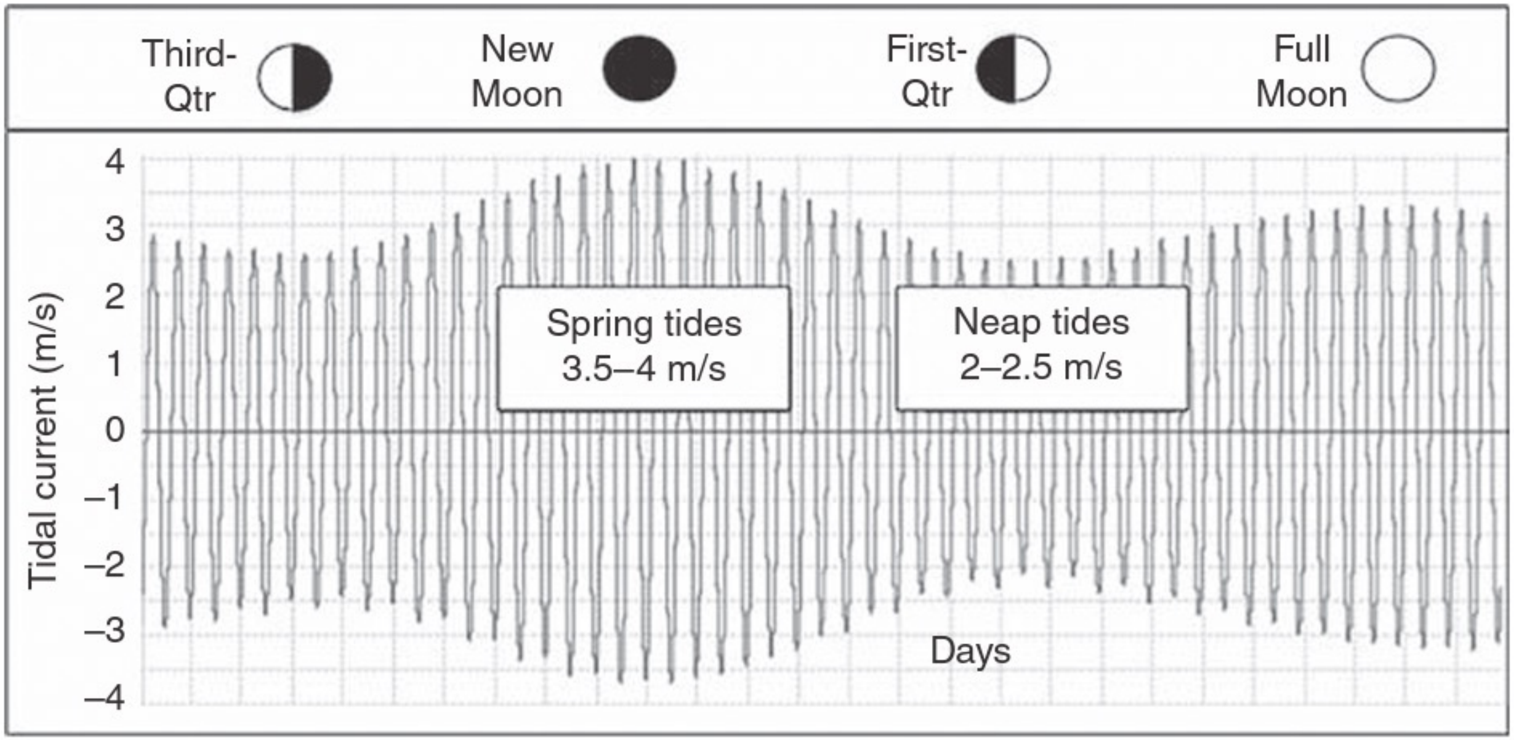


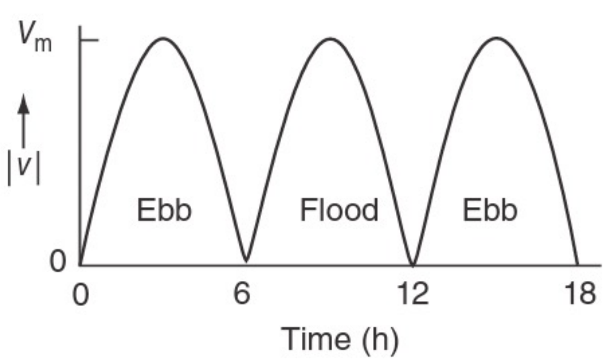
FIGURE 8.25 An example of the impact of spring and neap tides on tidal current.

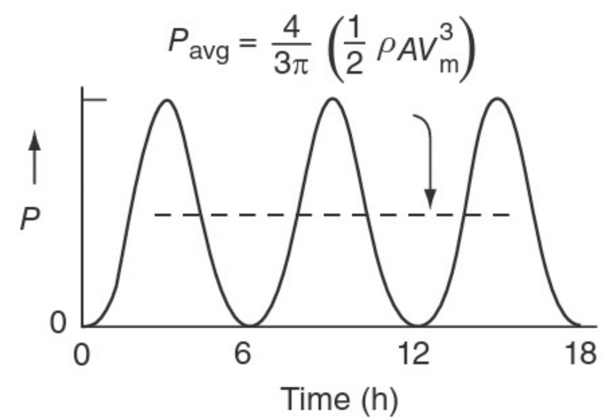
Estimating In-stream Tidal Power

$$P_{\text{avg}} = \left(\frac{1}{2}\rho A v^3\right)_{\text{avg}} = \frac{1}{2}\rho A \left(v^3\right)_{\text{avg}} \qquad v = V_{\text{m}} \sin(\omega t)$$

$$\Rightarrow \quad (v^3)_{\text{avg}} = \frac{1}{T}\int_0^T f(t)\mathrm{d}t = \frac{1}{\pi}\int_0^\pi (V_{\text{m}} \sin t)^3\, dt = \frac{4}{3\pi} V_{\text{m}}^3$$

$$\Rightarrow \quad P_{\text{avg}} = \frac{1}{2}\rho A \frac{4}{3\pi} V_{\text{m}}^3 = \frac{2}{3\pi}\rho A V_{\text{m}}^3$$

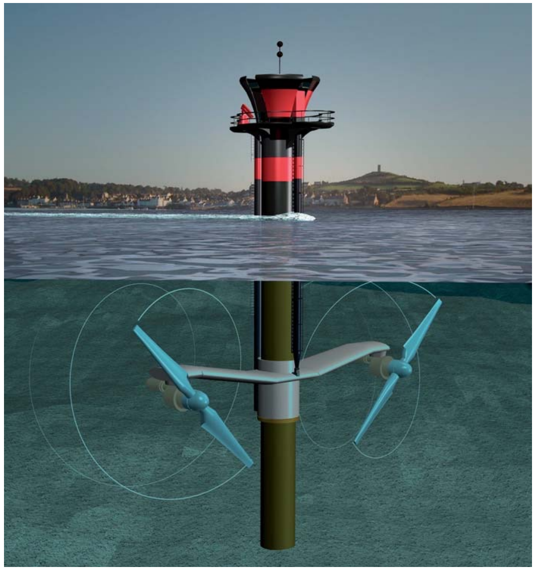




Tidal Energy Technologies

- Tidal energy include 1) kinetic energy obtained from the currents of changing tides; and 2) potential energy obtained from changing heights between the high and low tides.

- Technologies include tidal dams or barrages which contain a sluice across the water body. Beyond the sluice are hydro turbines. As the tide changes, the uneven water levels push through past the sluice and powers the turbine.



Advantages of Tidal Energy

- High efficiency of around 80%
- No GHG emissions

- Tidal stream generators have minimal environmental impact

- Low operations cost

- Reliable energy production (tides are constant & predictable)

- Very long lifespan (100+ years)

Read chapter 7 of textbook B3 !

[Tidal Power 101]