Tidal and wave power

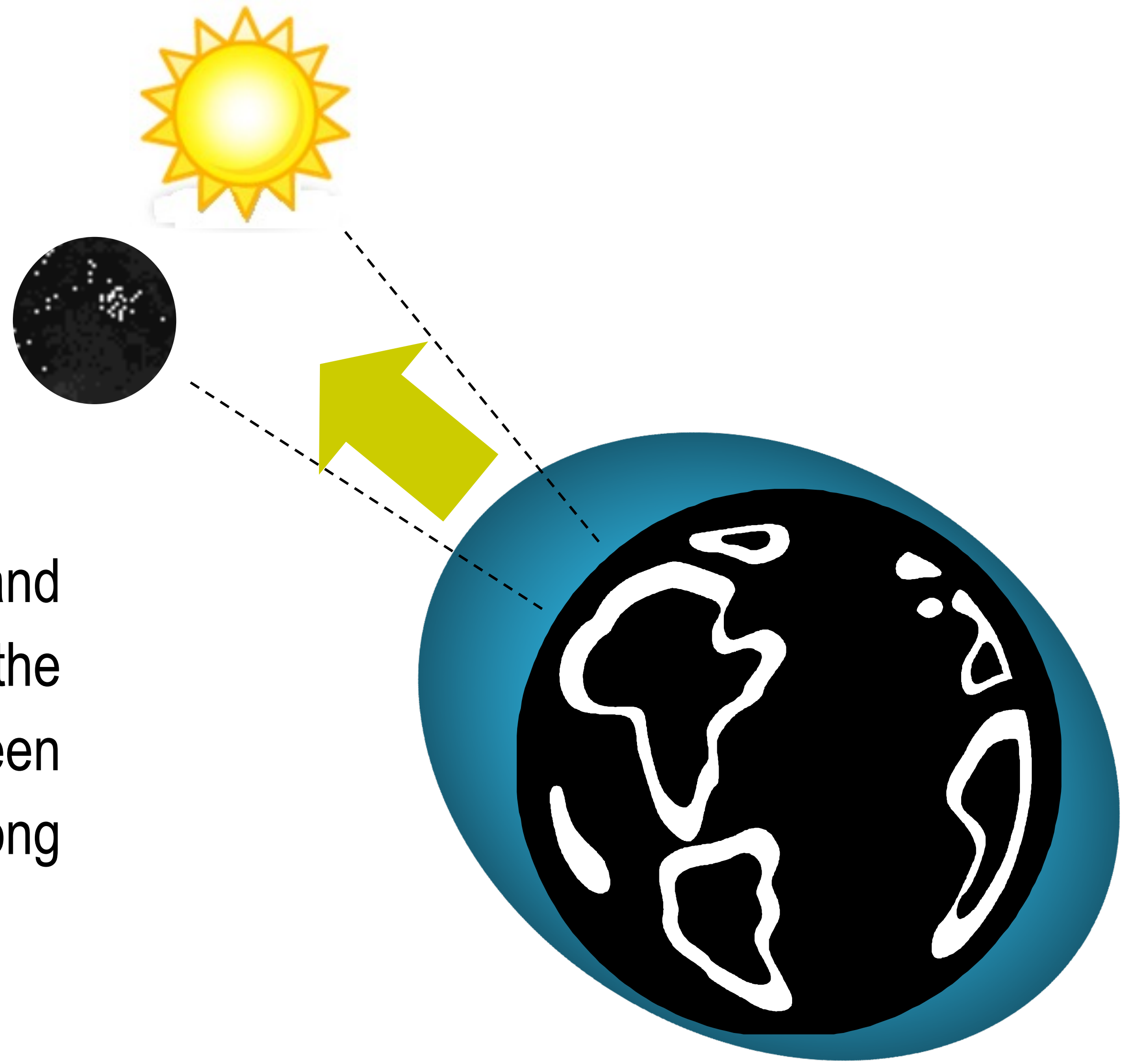
Learning objectives

- Explain the origin of tidal power, how we can exploit it, its advantages and its (real) potential
- Compare tidal turbines with wind turbines

- Explain the origin of wave power, how it is exploited, and its (real) potential

Tidal power

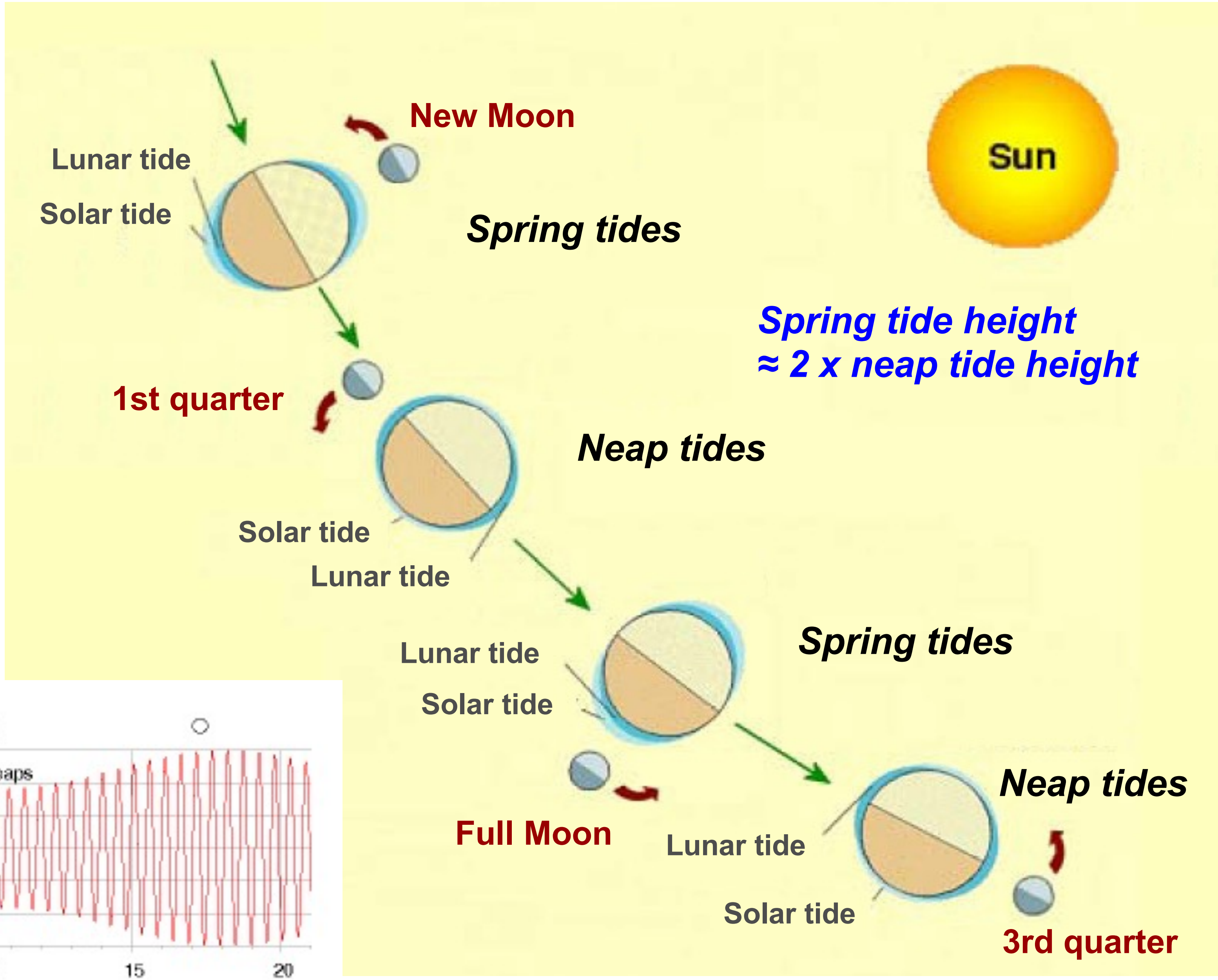
Tides result from the **sum** of gravitational pulls of the **Moon** and **Sun** on the surface of the spinning Earth.

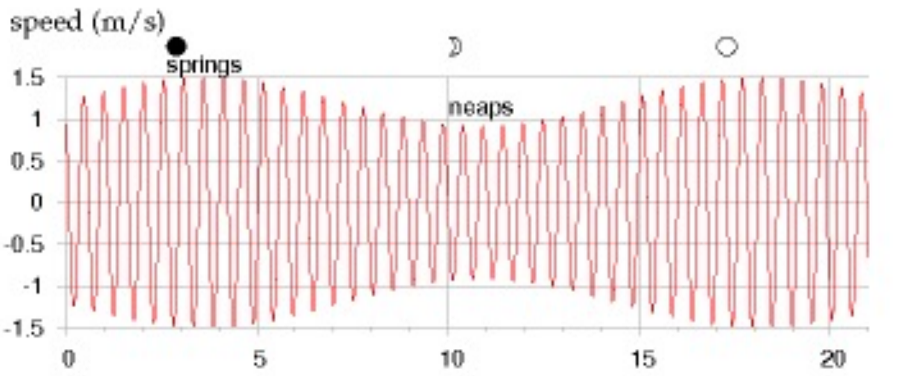


The shape of the shore and adjacent seafloor affects the **tidal range** (difference between high and low tides) along specific coast-lines.

The origin of tides

Earth orbits around its axis in 24h, while the Moon orbits around Earth in 28 days. Someone standing at the coast at not very high latitudes therefore sees 2 high tides and 2 low tides during one day (once every 6¼ h).





(a)

Explanations

- when Sun and Moon **align** to ‘pull’ **together** on the Oceans’ masses, tides are **heighest** and called ‘**spring**’ (New Moon, Full Moon)
- when Sun and Moon **misalign** ‘pulling’ on the Oceans’ masses at 90° angle (1st & 3rd quarter), tides are **lowest** and called ‘**neap**’.
- Earth orbits around its axis in 24 h, while the Moon orbits around Earth in 28 days; i.e. for 1 terrestrial day, the Moon is almost ‘stationary’ (it moves on 1/28th of its orbit, or by 360/28 = 13°)

⇒ a person standing at the coast at not very high latitudes sees **2 high tides and 2 low tides during one day** (once every ≈6¼ h).

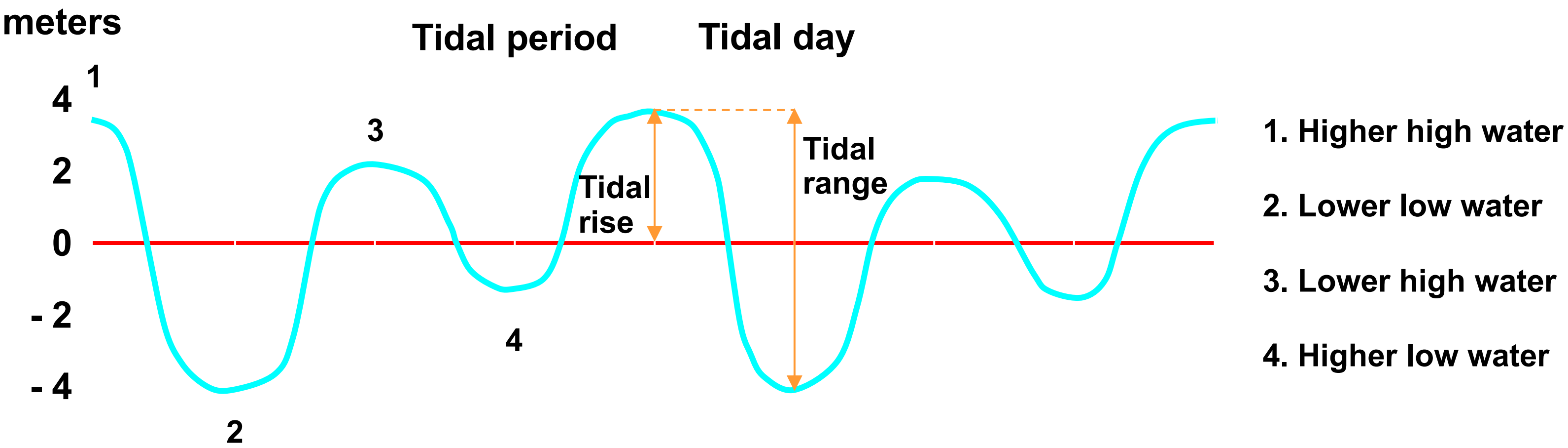
(it is ≈6¼h and not 6h because the Moon is not ‘stationary’: for the person to find the Moon in the same position he has to execute 1 rotation (2π rad) + x rad where

$$t[day] = \frac{x[rad]}{\omega_{Moon}[rad/day]} = \frac{(2\pi + x[rad])}{\omega_{Earth}[rad/day]} \quad \Rightarrow \quad t = \frac{28}{27} day = 24.89h$$

$$\Rightarrow \quad 1\ tide = \frac{24.89}{4} h = 6.22h = 6h13m20s$$

Tide mechanism

'Tides' = twice-daily rises and falls of water level relative to land



The **Coriolis** force makes the tidal range larger at **West** banks than at East banks (i.e. higher at the European Atlantic Coast than at the American Atlantic Coast).

Gravitational forces of Moon and Sun

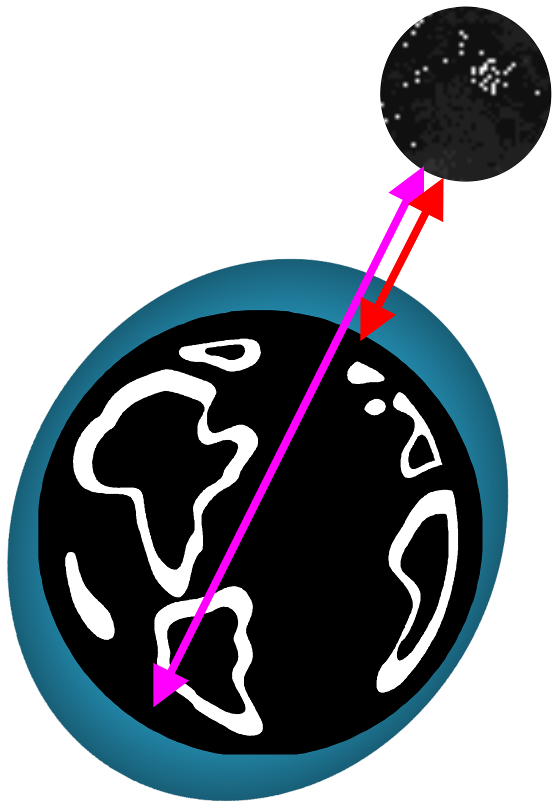
Newton's Law of gravitation : $$F = G\frac{M_1 M_2}{d^2}$$

G = 6.674 x 10^{-11} N m^2 kg^{-2}, universal gravitational constant
M_{Sun} = 1.989 x 10^{30} kg (333'000 x Earth's mass)
M_{Earth} = 5.9736 x 10^{24} kg
M_{Moon} = 7.3477 x 10^{22} kg (1.2% of Earth's mass)
$d_{Earth\text{-}Sun}$ = 1.496 x 10^{11} m (150 million km)
$d_{Earth\text{-}Moon}$ = 3.843 x 10^{8} m (0.384 million km)

→ $F_{Sun\text{-}Earth}$ = 3.54 x 10^{22} N
→ $F_{Moon\text{-}Earth}$ = 1.98 x 10^{20} N

Ratio of the forces of gravity : 'Sun-Earth' = 179 * 'Moon-Earth'

It's the difference of gravity between 'near' and 'far' side of the Earth that counts



Earth diameter = 12.756 10^6 m

Near side of Earth is 12756 km closer to both the Sun and the Moon than its **far** side.

$d_{Earth\text{-}Sun}$ = 1.496 x 10^{11} m

→ $\Delta d_{near\text{-}far}$ = 0.00856 % → $\Delta F_{near\text{-}far}$ = 0.0173% (*square* of distance dependence)

$d_{Earth\text{-}Moon}$ = 3.843 x 10^8 m

→ $\Delta d_{near\text{-}far}$ = 3.3% → $\Delta F_{near\text{-}far}$ = 7%

The acceleration force due to gravity of the Sun is 179 times that of the Moon. The **Sun's tidal effect** (the difference in force between far and near side of the Earth) is then 179 * 0.0173% **= 3.1%**, compared to the **Moon's (7%)**.

Hence total tidal force is for 2/3rd due to the Moon, and for 1/3rd due to the Sun.

Exploitation of tidal power

1. Based on **height difference**:
   - dams built in estuaries or coastal bays with important **tidal range**
   - so-called 'lagoons' built out in the sea

$$P = \rho_{H_2O} . \dot{V} g \Delta h$$

2. Based on the moving **water stream** :
   - different tidal stream turbine designs
   - = like 'underwater' **wind turbines**

$$P = \frac{1}{2} \rho_{H_2O} . C_P . A v_{H_2O}^3$$

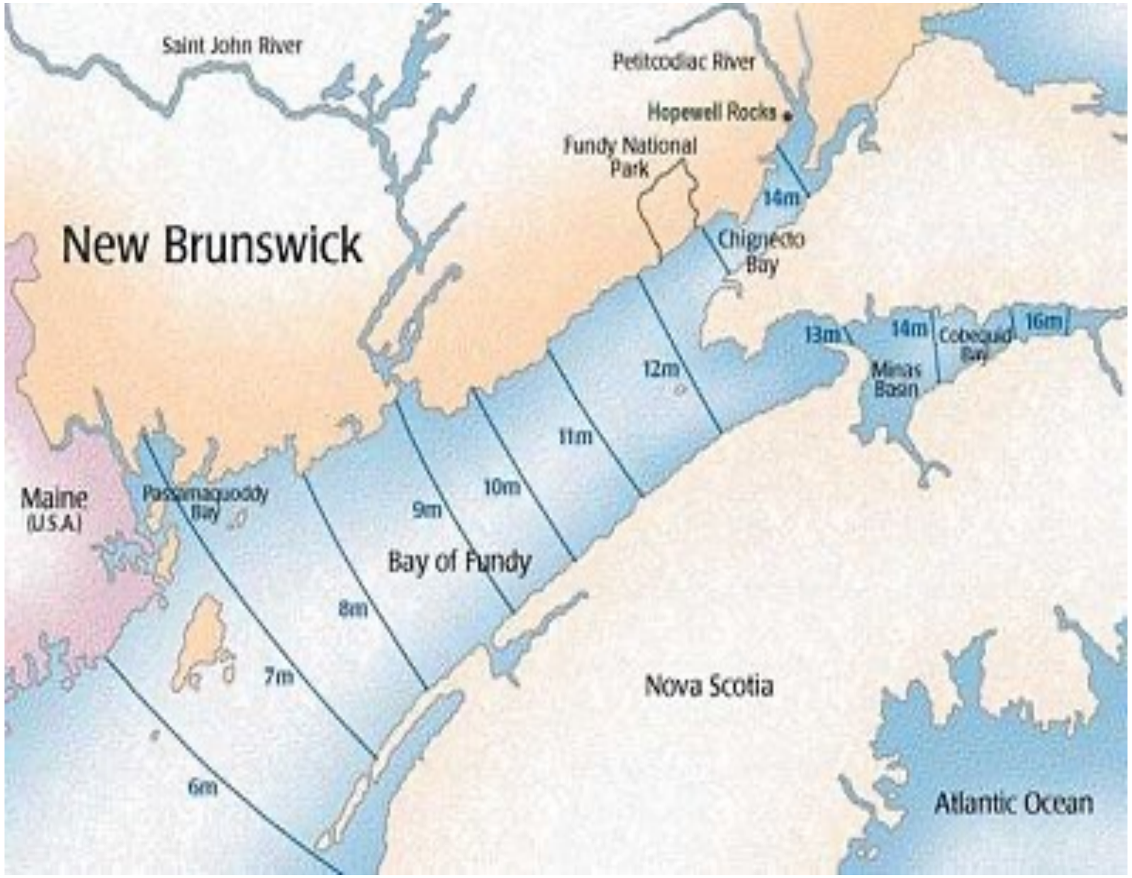
C_P: 20 to 50%, depending on design

v_{H_2O}: typically 1-2 m/s (ocean current)

Height difference: dams in bays

To be a practical source for electricity generation, the **tidal range** in a coastal area must typically be **at least 4 m**.

Only a handful of suitable tidal power station locations have been identified worldwide.

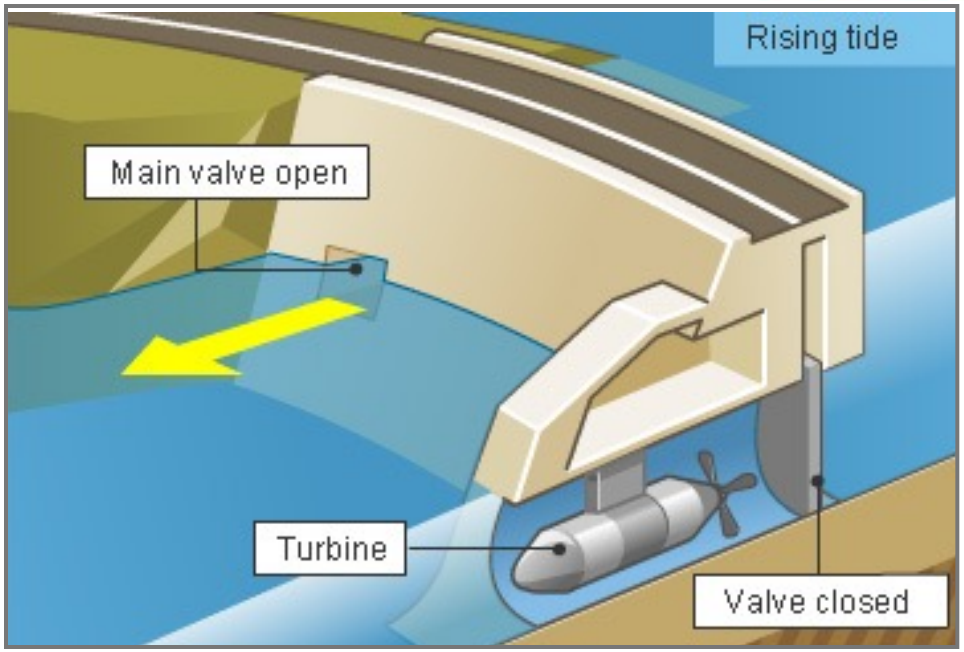


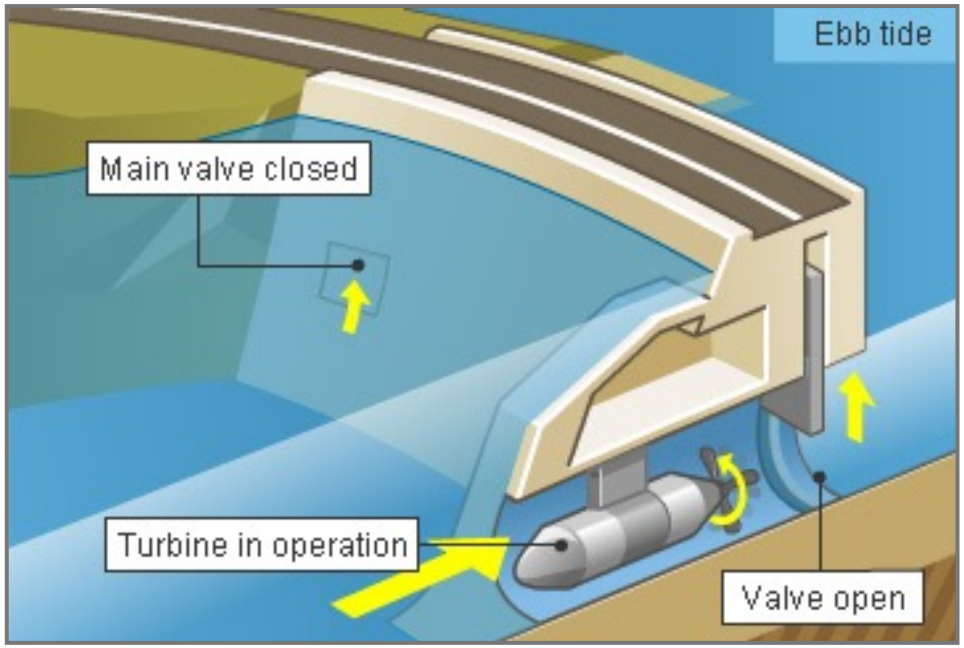
Theoretical world power in tides : 3000 GW

Actually exploitable : 120 – 400 GW

Actually running : 0.5 GW

Tidal power scheme

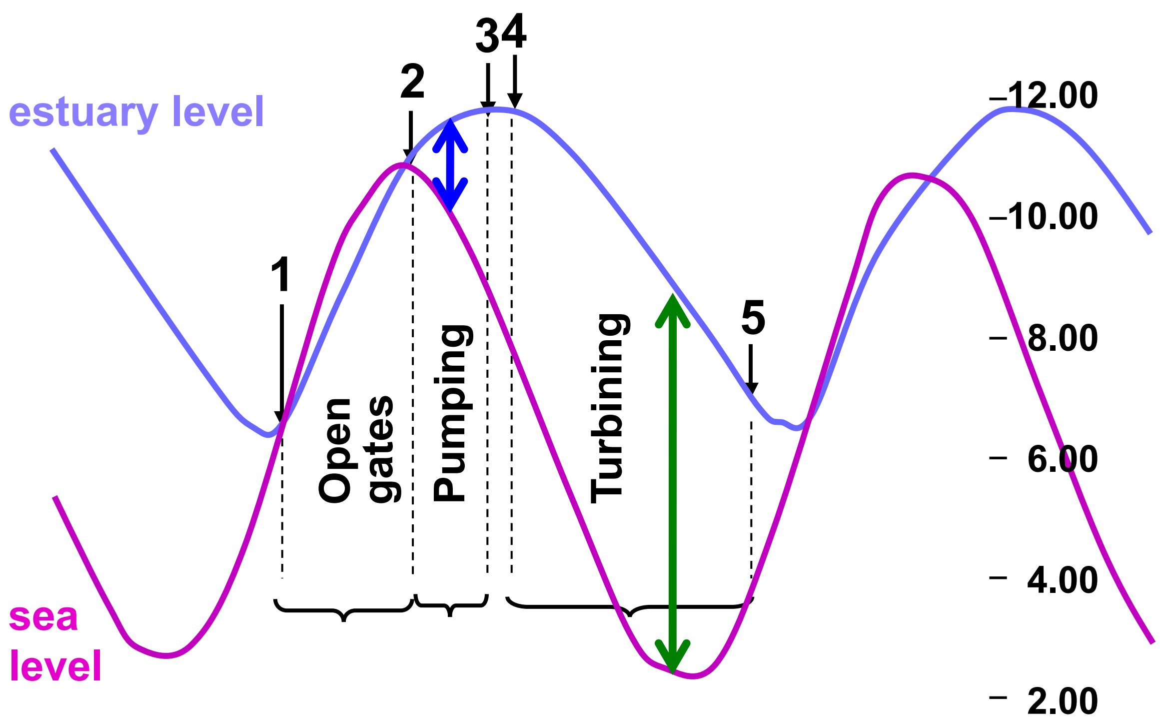




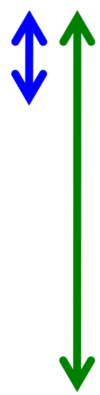
One-way / two-way exploitation

The variation of the sea level resulting from the tide movements can be exploited to produce electricity in two different ways: ***simple effect*** and ***double effect***

Simple effect: for middle tides or neap tides



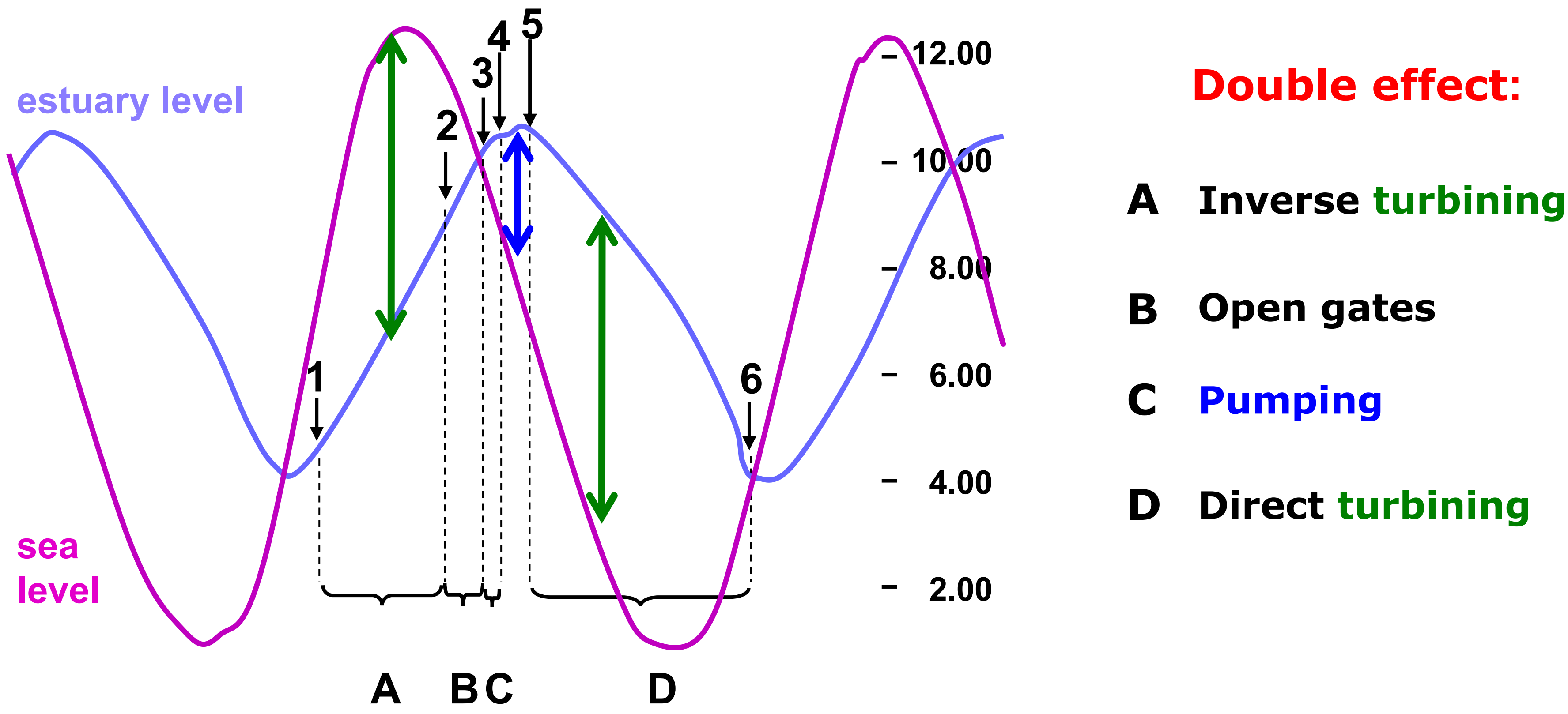
5 successive transitions per tide cycle



Power invested in **pumping** (small Δh) is only a fraction of the gain in **turbining** (larger Δh)

Double effect

For important tides, the use of the sea and estuary variation levels is based on a double effect cycle with 6 transitions per cycle.



Example : La Rance (F)

Largest and oldest commercial tidal power plant in operation

Construction: 1960 - 1967
Dam: 330 m long
Tide pool reservoir: 22 km^2
Average tidal range: 8 m (max 13.5 m)
24 Bulb turbines (5.4 m diameter), rated at 10 MW_e each (**240 MW_e** total), connected to the 225 kV French transmission network

La Rance (F) tidal power plant

The axial flow turbines allow generation on both floods and ebbs of the tide (**double effect**); they are also designed to **pump** water into the basin.

Number of units: 24

Installed power: **240 MW_e**

Net power**: 544 GWh/yr**

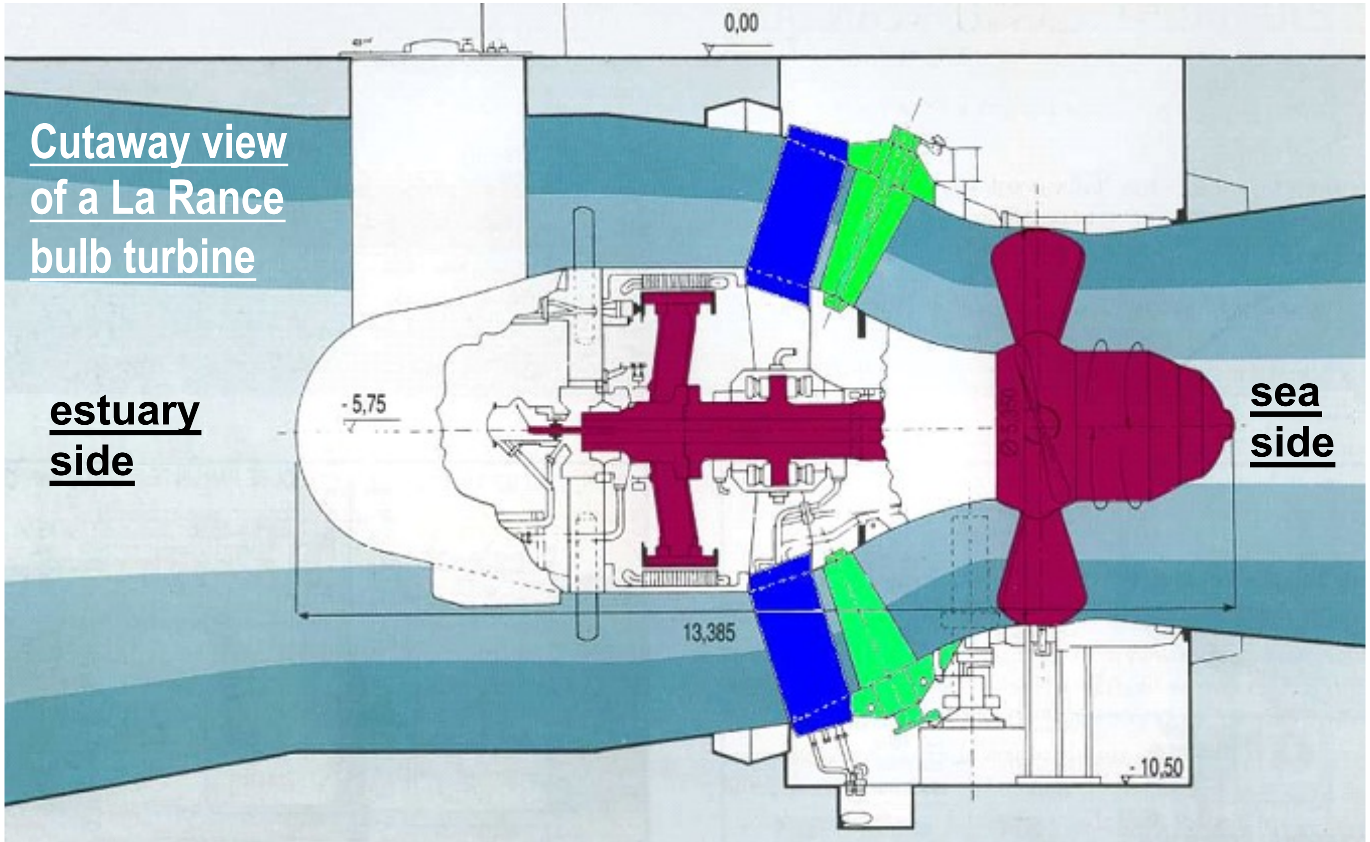
➔ avg power: **60 MW_e**

(taking year-round operation)

Turbines:
horizontal Kaplan
4 blades, blade inclination
-5° to + 35°

Alternators: rated power:
10 MW/unit

Output voltage: 3.5 kV

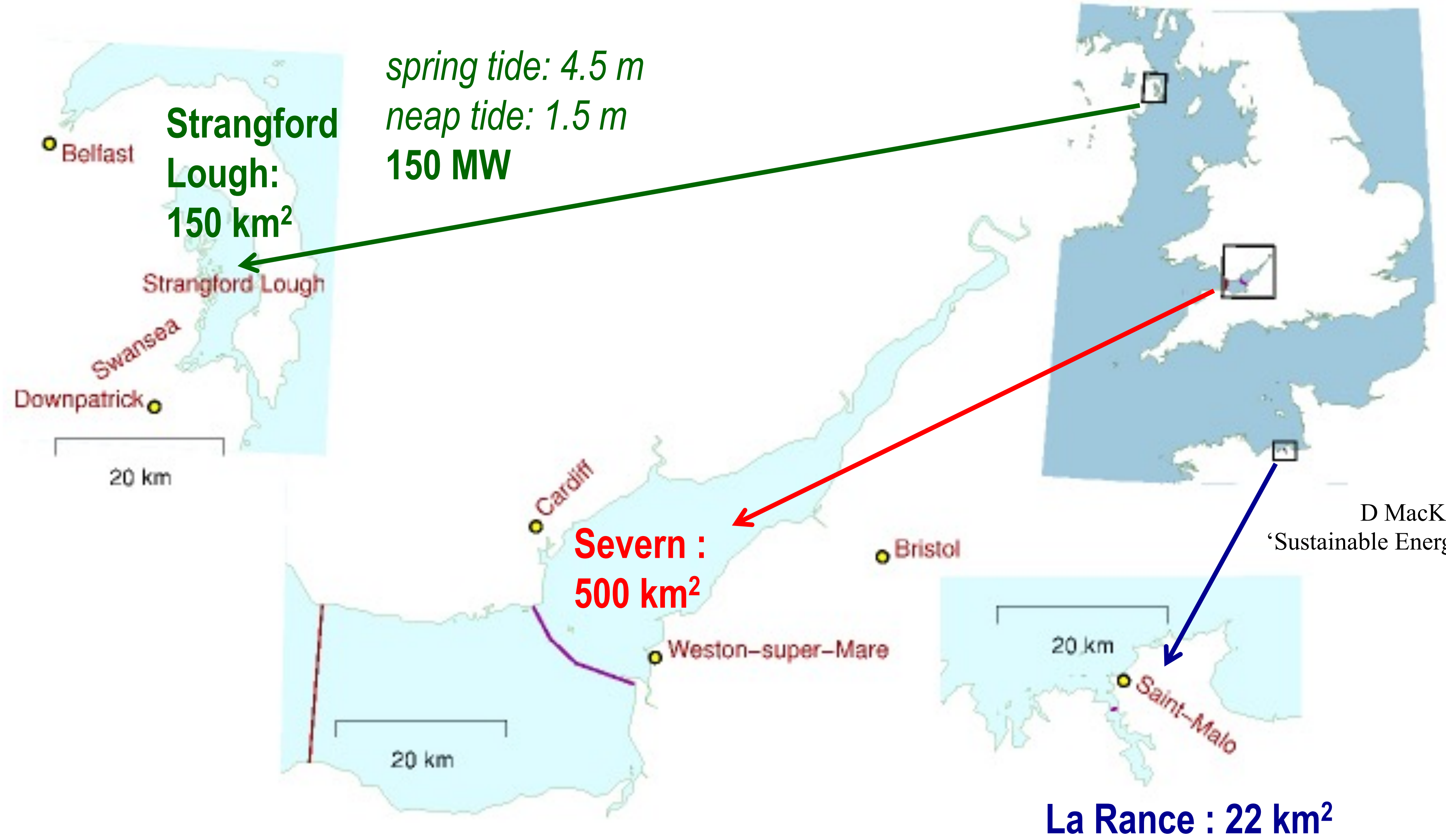


For comparison: Swiss electricity ~ 57 TWh ≈ 100 x La Rance

Example : UK

(Potential of 120 GW)

Other plants than La Rance (F) are operated in Canada and Russia, and others could be installed in certain other areas, e.g. the UK (Severn Barrage).

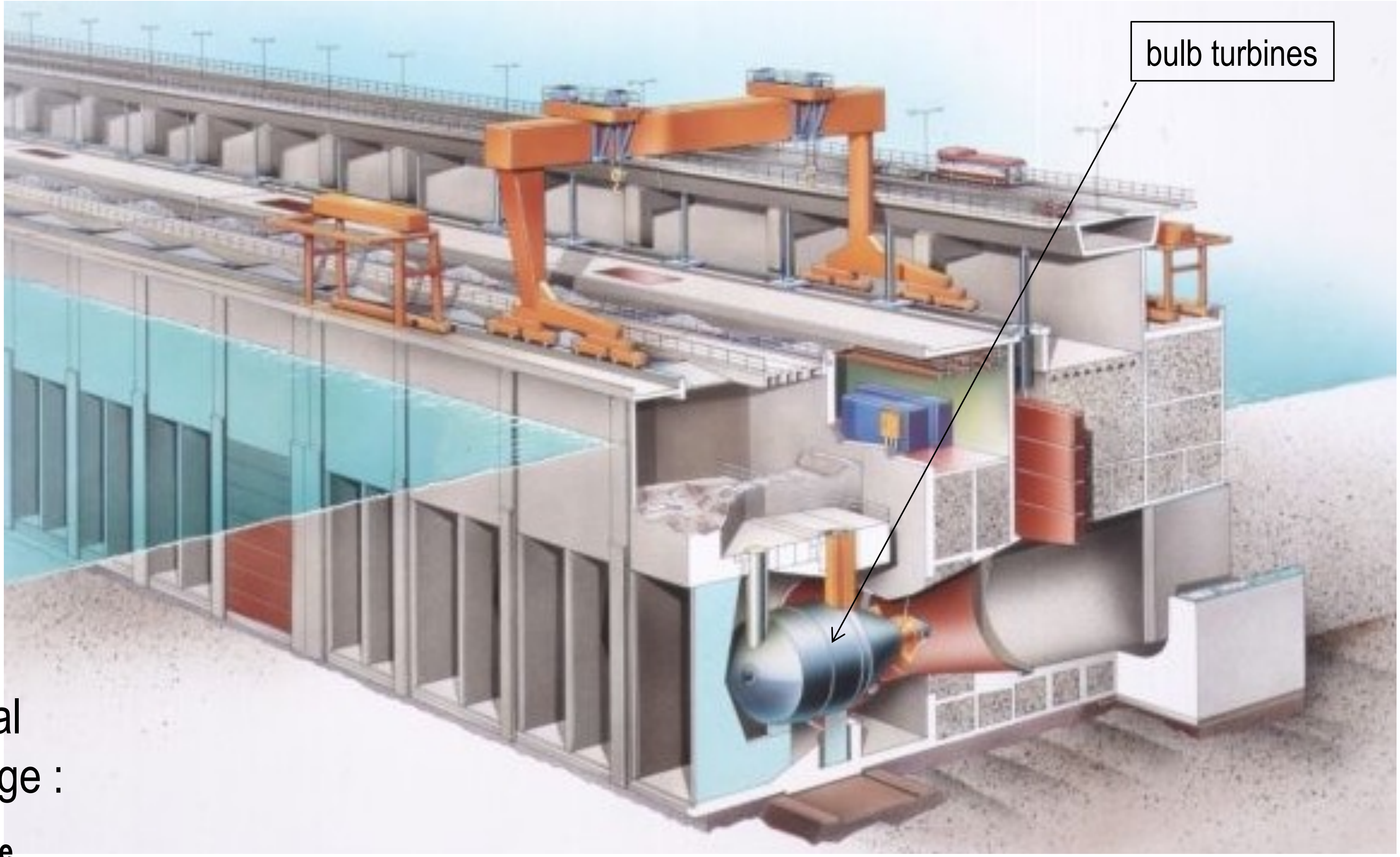


D MacKay, 'Sustainable Energy'

spring tide: 11 m => max **14.3 GW_e**

neap tide: 6 m => max **3.9 GW_e**

artist's impression of hypothetical Severn Barrage, UK



Annual average : **2 GW_e**

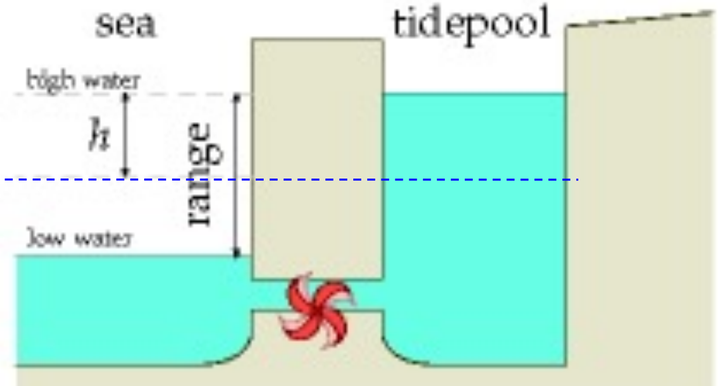
➔ **17 TWh / yr = 5% of UK electricity !**

Estimate of tidal range power

Potential energy: $E_{pot} = mgh$

mass centre

Mass per unit area (m²) in the tide pool : $m = \rho(2h)$



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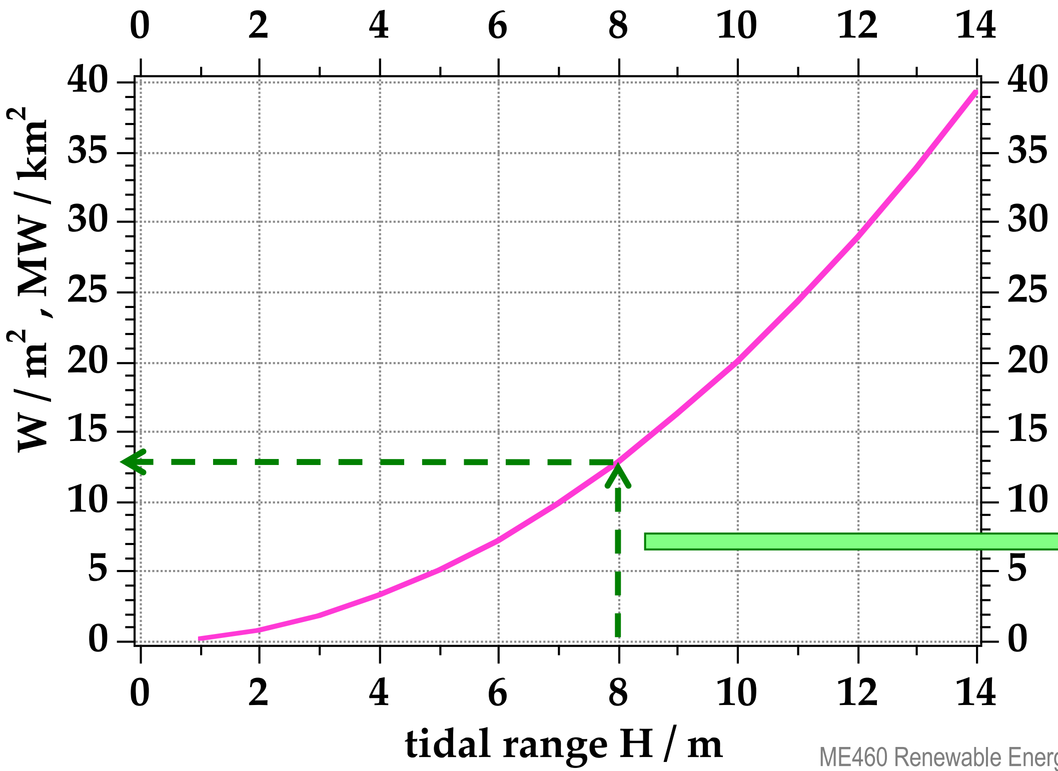
Power per unit area:
(double-effect generation)

$$P\left(W/m^2\right) = \frac{E_{pot}}{time} = \frac{\rho(2h)gh}{6.22\ hours} = \frac{19620\left[J/m^2\right]}{22400[s]}h^2 = 0.88\left(\frac{H}{2}\right)^2 = 0.22H^2\left[W/m^2\right]$$



turbining efficiency ≈90%

$$0.2H^2\left[\frac{MW_e}{km^2}\right]$$

La Rance : 8 m => 12 MW_e / km²
reservoir 22 km² => ≈ 260 MW_e

Tidal power 'on-stream'

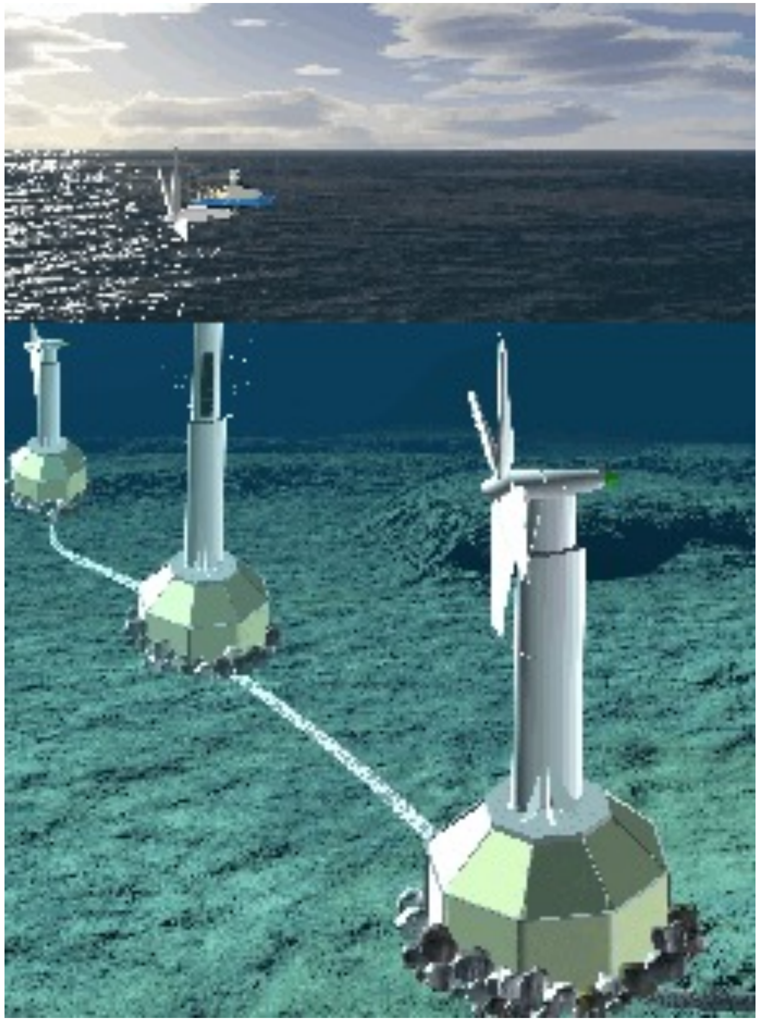
Tidal stream generators draw energy from underwater **currents** in much the same way that ***wind generators*** are powered by the wind.

The much higher **density** of water vs. air gives significant power to a single generator.

The technology is at the early stage of development and requires significantly more research.

Tidal power 'on-stream' : Swan-turbine

Particular type of tidal stream turbine



Blades are connected directly to the electrical generator, without a gearbox.

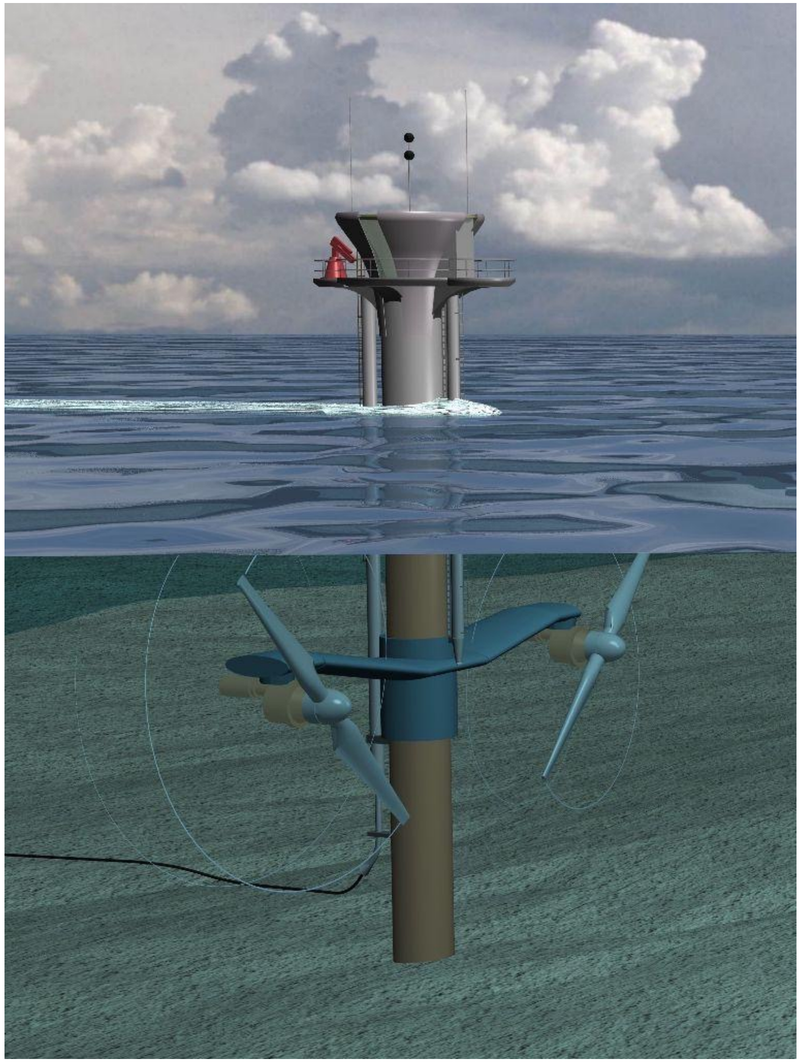
A "gravity base" large concrete block holds it to the seabed.

The blades are **fixed pitch** (more reliable), rather than actively controlled.

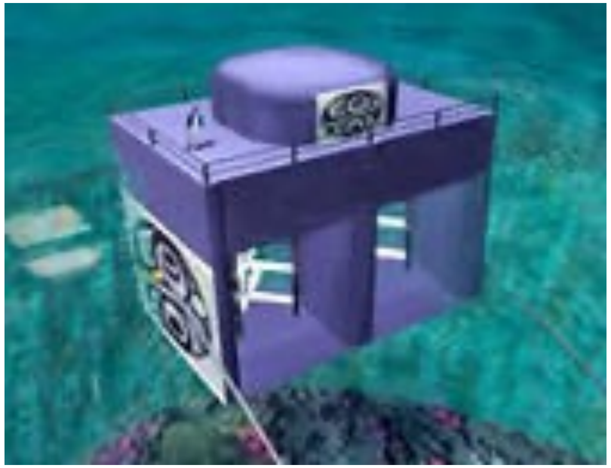
Tidal power ‘on-stream’ : sea-flow propeller

http://www.youtube.com/watch?v=lzc9-V9DSew&feature=related

Several prototypes have shown promise; in the UK, a **300 kW** Seaflow marine current propeller type turbine was first tested in 2003, followed by a **1.2 MW** SeaGen unit in Strangford Lough (Northern Ireland) in 2008.



‘Blue Energy’ (CAN) plans to install large array tidal current devices in 'tidal fences‘, based on a vertical axis turbine design

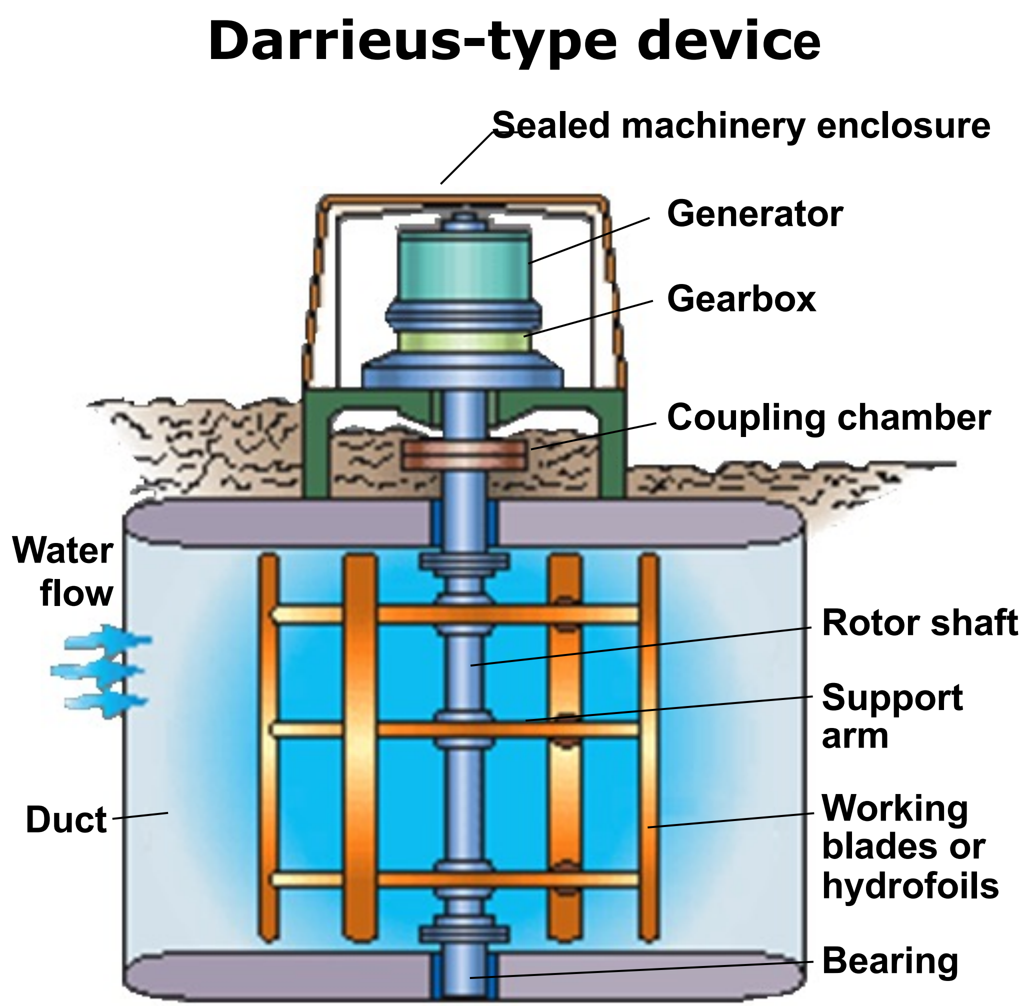


‘Darrieus’ tidal turbine

Four fixed vertical blades connect to a rotor shaft that drives an integrated gearbox/generator.

The turbine sits in a concrete marine casing; the casing directs water through the turbine and supports the generator and other machinery.

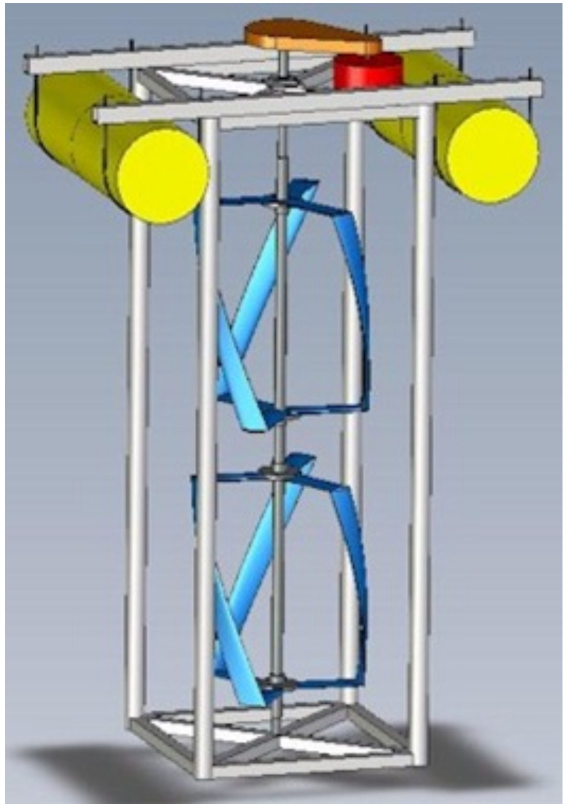
Water flowing either way spins the turbine, letting the unit generate power during a tide's ebb and flood.



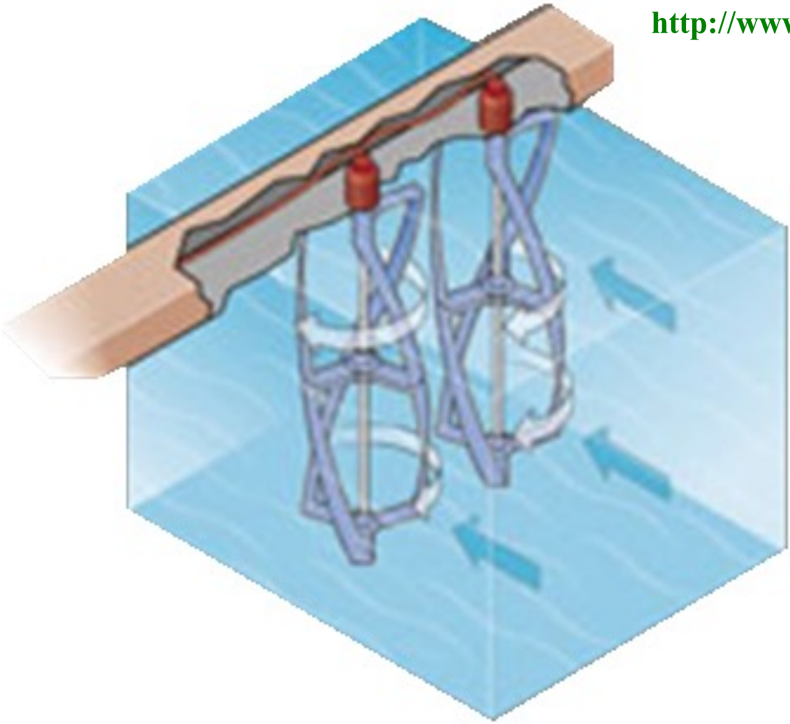
‘Gorlov’ helical tidal turbine

The turbine rotates regardless of the direction of the water current.

The Gorlov turbine captures 35% (=C_p) of the water energy, compared to 23% for a straight Darrieus turbine and 20% for a conventional turbine.



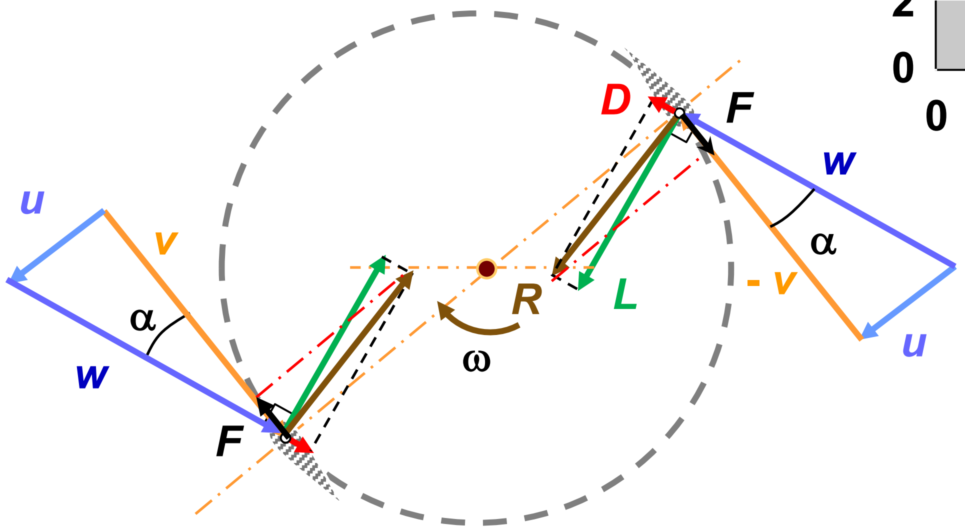
http://www.youtube.com/watch?v=zWu5auKHJzQ

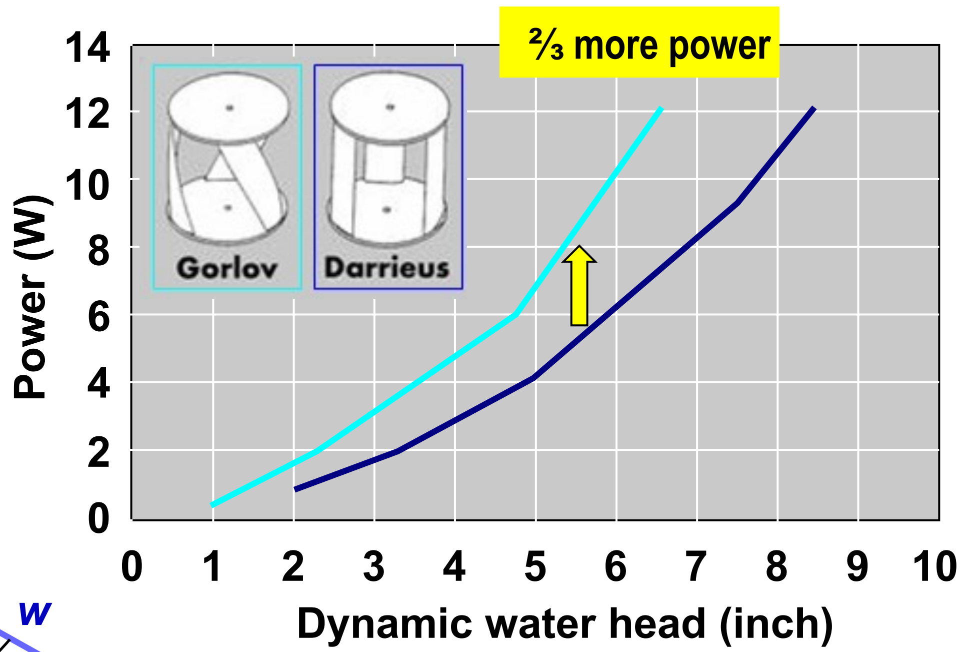


Relation to wind turbines

v : linear blade speed
U : water flow speed
w : relative speed
α : attack angle
L : lift
D : drag

(*v*, *U*, *w*: speed triangle)





http://www.youtube.com/watch?v=XnylCf5w0PQ

Propulsion force:

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

Estimate of tidal power (UK)

D MacKay, 'Sustainable Energy'

We want to estimate the power extractable from an underwater turbine farm that occupies a certain (sub)surface of the ocean.

In 1st approximation, we use the formula

$$P\left[\frac{W}{m^2_{Turbine\_area}}\right] = \frac{1}{2}\rho_{H_2O}.C_P.Av^3_{H_2O}$$

assuming Cp ≈ 35% and where v can be 0.5 m/s to 5 m/s (typically : 1 m/s).
<u>Remark</u> : 1 "knot" = 0.5 m/s

The turbines should be spaced apart by minimum 5 diameters to their neighbours, i.e. each turbine would occupy an area of $25\bullet D^2 = 100\bullet A / \pi$
(since $A = \pi\bullet D^2 / 4$)

This leads to the simplified expression:

$$P\left[\frac{W}{m^2_{ocean-subsurface}}\right] = \frac{0.5 \bullet 1000 \bullet 0.35 \bullet A \bullet v^3}{\frac{100 \bullet A}{\pi}} = 5\pi \bullet 0.35 \bullet v^3 \approx 5.5v^3$$

This is **substantial power** !

Placing a sea-turbine farm over an area of 1 km² (e.g. 100 rows by 100 columns of turbines (10'000 turbines!) of 4 m², D=2 m, spaced 5D=10 m apart) in a location where **ocean current** is 2 m/s (7 km/h), will generate 44 MW_e of electrical power (4.4 kW_e per turbine). (The equivalent **wind** turbine of 4 m², even at avg v^3 = 1000 m^3/s^3, would generate <1 kW_e, i.e. **5 times less**)

Speed v (m/s)	Power W / m²
0.5	0.7
1	5.5
2	44
3	150
4	350
5	687

It is moreover argued that tidal current in shallow water (i.e with depth *d* of the same magnitude as the length of the wave (λ), typically 100 m) can be derived to be (*cf. « Wave-power »* chapter):

$$P_{tidal}\left[\frac{W}{m}\right]_{shallow\_water} = \frac{1}{2}\rho g^{3/2} d^{1/2} y_0^2 \approx 153'630 \bullet y_0^2$$

≈ λ (for d)

y_0: wave amplitude, typically 1 m (waveheight = $2y_0$)

d = 100 m

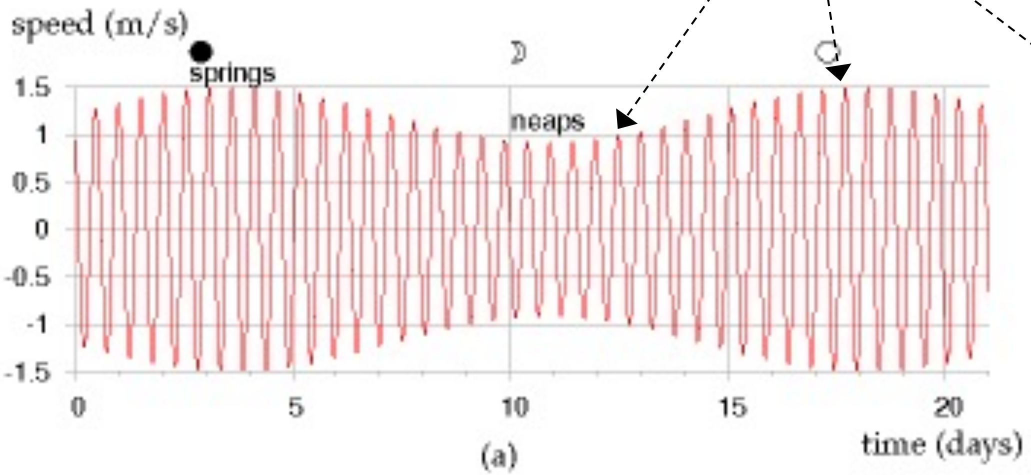
y_0, Wave amplitude (m)	Power kW / m wavewidth
0.5	38
1	153
1.5	345
2	615

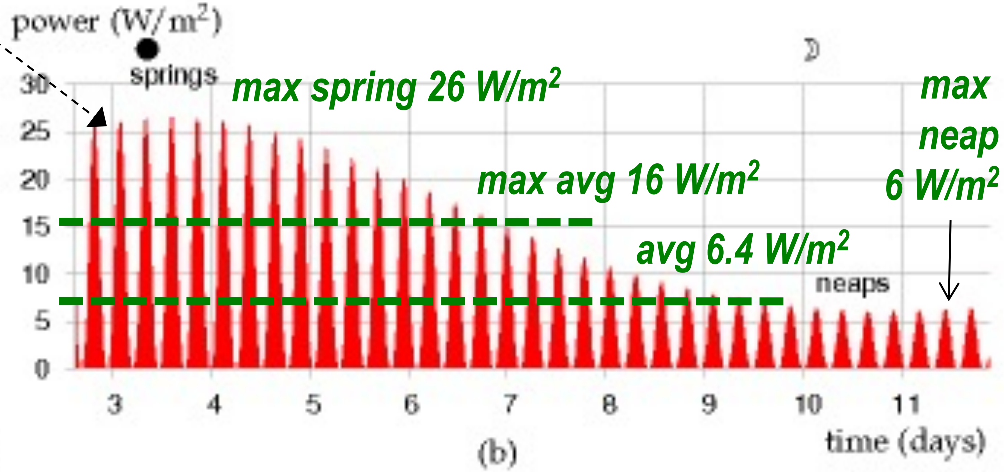
This is again **substantial power**, some **5 times bigger than wave**-power (which is **wind**-derived, not tidal).

Tidal stream farm

The sea-turbine power values (W per m^2 of seafloor) even with only 1-2 m/s ocean current are only **peak** values.

D MacKay, 'Sustainable Energy'





Due to the sinusoidal back-and-forth rocking of tides every 6h, the average effective current is ≈ 0.4•peak current.
At neap tide, power is further reduced.

max spring power = 4 x max neap power

average max power = (spring$_{max}$ + neap$_{max}$) / 2

average power (W/m^2) = 0.4 • avg max power

Advantages of tidal power

- entirely predictable; reliable; year-round operation
- known hardware; but with challenges:
  - salt corrosion
  - silt accumulation
  - entanglement of floating matter
  - ….
- in particular when comparing **tidal** turbines **vs. wind** turbines:
  - no visual impact !
  - low turbine safety factor needed

    (there are no underwater tidal 'storms' as opposed to wind storms)
  - smaller turbines for the same power, due to $\rho_{H_2O} >> \rho_{air}$

Wave power

Wave power: origin and characteristics

Ocean surface wave motion is **3rd generation sun power**: sun heat creates the winds, and **winds create the waves**.

The **wavelength** λ (m) and **period** T (s) depend on the **windspeed**.
The **height h** of the wave depends on the **time** the wind has been blowing!
Like with wind, you can extract power only once.

The potential is especially interesting on the Atlantic (direction west→east); the feasibility of wave power is therefore especially investigated in the UK.

Power Generators :
= either coupled to ***floating*** devices (oscillating buoys)
= or turned by ***air***, ***displaced*** by waves in a hollow concrete structure

Numerous practical problems exist

- Total theoretical power potential estimated 2000 GW, the recoverable part to 300-500 GW
- Total theoretical energy potential estimated to 8000 – 80'000 TWh/year, the actual recoverable part to 1200 TWh/yr

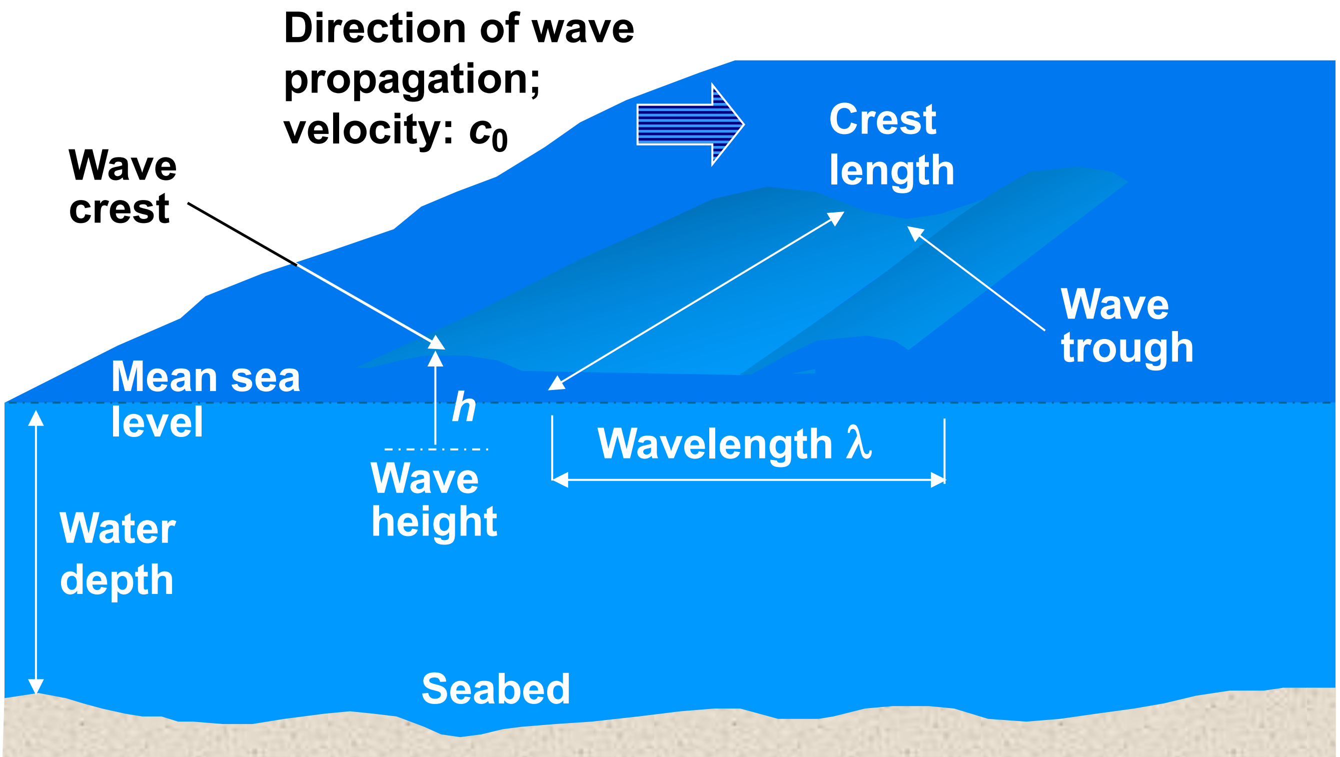
Source: Sustainability **2020**, *12*, 2178
Electrical Power Generation from the Oceanic Wave for Sustainable Advancement in Renewable Energy Technologies

RESs	Year-2017	Year-2018
Hydropower (GW)	1112	1132
Wind power (GW)	540	591
Solar PV (GW)	405	505
Bio-power (GW)	121	130
Geothermal power (GW)	12.8	13.3
Concentrating solar thermal power (GW)	4.9	5.5
Ocean power (GW)	0.5	0.5
Total (GW)	2196.2	2377.3

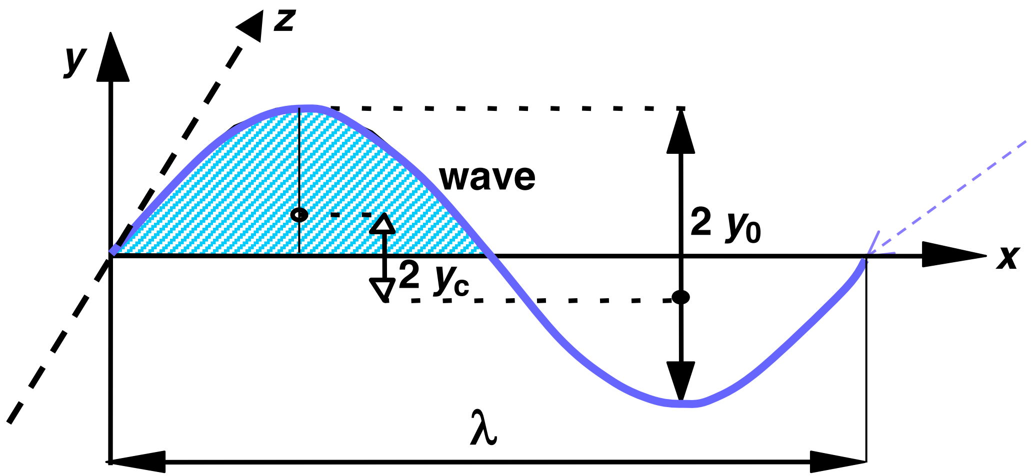
Energy stored in ocean surface waves: calculation

Two components:

- *kinetic* (horizontal: water flow)
- *potential* (vertical: level difference between crest and trough of the wave)



The energy that can be extracted from a wave corresponds roughly to the **potential energy liberated by the collapse of the wave** crest, i.e. the energy obtained when the mass M of the "half-wave" falls from a **height 2 y_c**, where y_c represents the mass centre of the "half-wave".



assume $y = y_0 \cdot \sin(2\pi x/\lambda)$

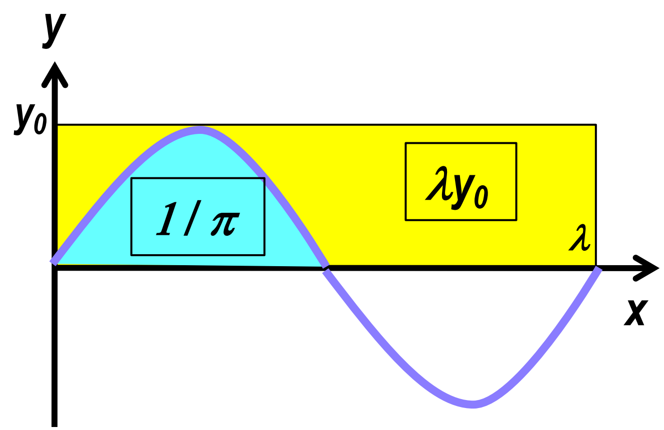
$2\,y_0$: double amplitude of the wave (= h)

$2\,y_c$: level difference between the half-waves mass centres

Mass M_z per unit length of the wave front in z-direction (kg/m):

$$M_z = \rho \int_0^{\lambda/2} \int_0^{y_0 \sin(2\pi x/\lambda)} dy\,dx = \rho \int_0^{\lambda/2} y_0 \sin(2\pi x/\lambda)\,dx = \boxed{\rho \frac{\lambda y_0}{\pi}}$$

$$\rho y_0 \left[-\cos\left(\frac{2\pi x}{\lambda}\right) \frac{\lambda}{2\pi} \right]_0^{\lambda/2} = \rho y_0 \frac{\lambda}{2\pi} \underbrace{\left[-\cos\pi + \cos 0 \right]}_{=2}$$



Position y_c of the mass centre = ? :

$$M_z = \frac{\rho y_0 \lambda}{\pi}$$

$$y_c = \frac{\rho \int_0^{\lambda/2} \int_0^{y_0 \sin(2\pi x/\lambda)} y\,dy\,dx}{\rho \int_0^{\lambda/2} \int_0^{y_0 \sin(2\pi x/\lambda)} dy\,dx} = \frac{\rho \int_0^{\lambda/2} \int_0^{y_0 \sin(2\pi x/\lambda)} y\,dy\,dx}{M_z} = \frac{\rho}{\frac{\rho y_0 \lambda}{\pi}} \int_0^{\lambda/2} \left. \frac{y^2}{2} \right]_0^{y_0 \sin(2\pi x/\lambda)} dx$$

$$y_c = \frac{\pi}{y_0 \lambda} \int_0^{\lambda/2} \left(\frac{y_0^2}{2} \right) \sin^2(2\pi x/\lambda)\,dx = \frac{\pi y_0}{2\lambda} \int_0^{\lambda/2} \sin^2(2\pi x/\lambda)\,dx$$

$$\int \sin^2(x)\,dx = \tfrac{1}{2} \int (1 - \cos(2x))\,dx$$

because:

$$\cos(2x) = \cos^2(x) - \sin^2(x)$$

$$\cos^2(x) + \sin^2(x) = 1$$

$$\int \sin^2\left(\frac{2\pi x}{\lambda}\right) dx = \tfrac{1}{2} \int \left(1 - \cos\left(\frac{4\pi x}{\lambda}\right) \right) dx$$

Substitute: $t = \frac{4\pi x}{\lambda}, \quad dt = \frac{4\pi}{\lambda} dx, \quad dx = \frac{\lambda}{4\pi} dt$

$$\rightarrow \quad \tfrac{1}{2} \int dx - \tfrac{1}{2} \int \frac{\lambda}{4\pi} \cos(t)\,dt = \frac{x}{2} - \frac{\lambda}{8\pi} \int \cos(t)\,dt$$

$$\left(\frac{x}{2} - \frac{\lambda}{8\pi} \sin(t) \right) \Bigg|_0^{\lambda/2} = \left(\frac{x}{2} - \frac{\lambda}{8\pi} \sin\left(\frac{4\pi x}{\lambda}\right) \right) \Bigg|_0^{\lambda/2} = \frac{\lambda}{4} - 0 - \frac{\lambda}{8\pi} (\sin 2\pi - \sin 0) = \frac{\lambda}{4}$$

$$y_c = \frac{\pi y_0}{2\lambda} \cdot \frac{\lambda}{4}$$

$$y_c = \frac{\pi y_0}{8} \approx 0.39 y_0$$

➔ *Energy* stored in ocean surface waves: result

Total energy W (=m.g.h) *per unit length (=Joule/m)* of the wave *front (=z)* due to the collapse of the wave, generated during time of passage of the wave (period T):

$$W_{wave} = M_z \cdot g \cdot 2y_c = 2\frac{\rho \cdot y_0 \cdot \lambda}{\pi} \cdot g \cdot \frac{\pi \cdot y_0}{8} = \frac{\rho \cdot g \cdot y_0^2 \cdot \lambda}{4}$$

Wave characteristics, e.g.:

$\lambda = 100$ m

$y_0 = 1$ m

→ **W = 250 kJ / m**

How to compute the *power* in a wave? (*=W_{wave} / T*) (T=period)

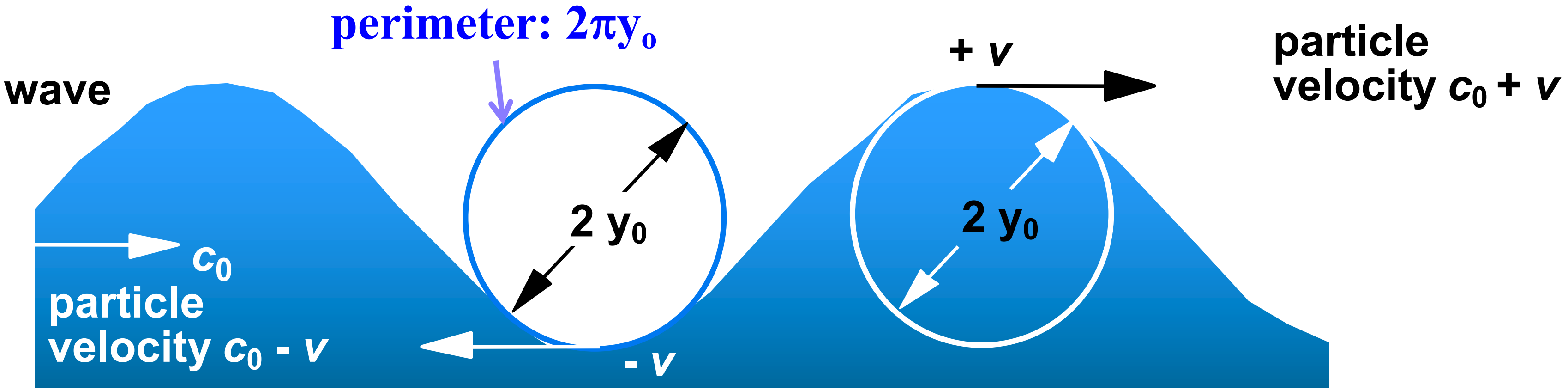
- The water particles move themselves (= **kinetic** energy) but at much lower speed, v, than the wave, c_0 (as demonstrated by the slow movement of objects floating on water, 'under' which the waves travel faster).

⇒ we need to know this **speed v** with which the water itself moves (≠ **wave speed c_0** = λ / T !), in order to find an expression for T

⇒ a relation between the water velocity v and the wavelength λ can be physically derived (next slide)

Correlation between water velocity v and wavelength λ:

Consider a reference frame in movement with the wave: cylindrical surfaces, tangential to the trough and crest of the wave respectively, rotating with the angular velocity $\nu = c_0/\lambda$ = 1/T = v / ($2\pi y_0$) (=> speed $v = 2\pi y_0 \nu$) *
(The speed ratio of 'wave' vs. 'water'
= c_0/v = $\lambda/2\pi y_0$ = wavelength vs. ≈ (π • waveheight))
We then calculate the difference in **kinetic** energy of the water particles at the wave crest and in the trough: E_{kin} (out – in) = 2.v



*physical explanation: During the time that 1 wave travels through, i.e. T(in seconds) = (1/angular speed) = wave lenght λ /wave_speed c_0, the cylinder has rolled around its perimeter π*2y0

Kinetic & potential energy of the water in the wave:

Variation of the **kinetic** energy of the water particles:

speed $v = 2\pi y_0 \nu$

c_0/λ

$$\Delta w_{kin,\ water} = m \cdot c_0 \cdot 2v = m \cdot c_0 \cdot 2 \cdot 2\pi \cdot y_0 \cdot \nu = (4 \cdot m \cdot c_0^2 \cdot \pi \cdot y_0)/\lambda$$

$$E_{kin,out} - E_{kin,in} = \left[\frac{1}{2}m(c_0+v)^2 - \frac{1}{2}m(c_0-v)^2\right] = \frac{1}{2}m(2c_0v - (-2c_0v)) = 2mc_0v$$

<u>cf. Euler equation</u> : specific mass energy w (J/kg) = $v_e.\Delta v_t$

= entrainment velocity * (tangential velocity difference out-in) = c_0 * 2v

Corresponding variation of the **potential** energy of the water particles: $\Delta w_{pot,\ water} = m \cdot g \cdot 2 \cdot y_0$

Since $\Delta w_{kin,\ water} = \Delta w_{pot,\ water}$ (like for all *oscillating* movement), we can derive:

$$\frac{4mc_0^2\pi y_0}{\lambda} = 2mgy_0 \Rightarrow c_0^2 = \frac{g\lambda}{2\pi} \Rightarrow c_0 = \left(\frac{g\lambda}{2\pi}\right)^{1/2}$$

$$\frac{2\pi}{g}c_0 = \frac{\lambda}{c_0} = T = 0.64\ c_0$$

wave period T (s)

$$T = \frac{\lambda}{c_0} = \frac{\lambda}{\sqrt{g\lambda/2\pi}} = \left(\frac{2\pi\lambda}{g}\right)^{1/2} = \sqrt{0.64 \bullet \lambda}$$

=> *power* *P* in the wave (W_{wave} / *T*) : result

The *energy* per unit length of the wave front (J/m) was found before as:

$$W_{wave} = \frac{\rho \cdot g \cdot y_0^2 \cdot \lambda}{4}$$

The *power* per unit length of the wave front (W/m) is then this wave *energy* (J/m) divided by the period T (s), found on the previous slide:

$$\Rightarrow \quad P_{wave} = \frac{W_{wave}[J]}{T[s]} = \frac{\rho g y_0^2 \lambda / 4}{\sqrt{\frac{2\pi\lambda}{g}}} = \frac{\rho g^{3/2}}{4\sqrt{2\pi}} y_0^2 \sqrt{\lambda} \approx 3064 \bullet y_0^2 \sqrt{\lambda}$$

const: 3064

power per unit length (W/m) of the wave front

=> numerical application:

P [W/m] = $3064 \cdot y_0^2 \cdot \lambda^{1/2}$ (y_0, λ in m)

Wave characteristics:

λ = 100 m

y_0 = 1 m

waveheight = 2 m

T = 8 s, ν = 1 / 8

c_0 = 12.5 m/s

v = 0.8 m/s

***P* = 30 kW / m**

D MacKay, 'Sustainable Energy'

30 GW ?

$$T = \frac{2\pi}{g} c_0 = 0.64 c_0$$

$$\lambda = \frac{2\pi}{g} c_0^2 = 0.64 c_0^2$$

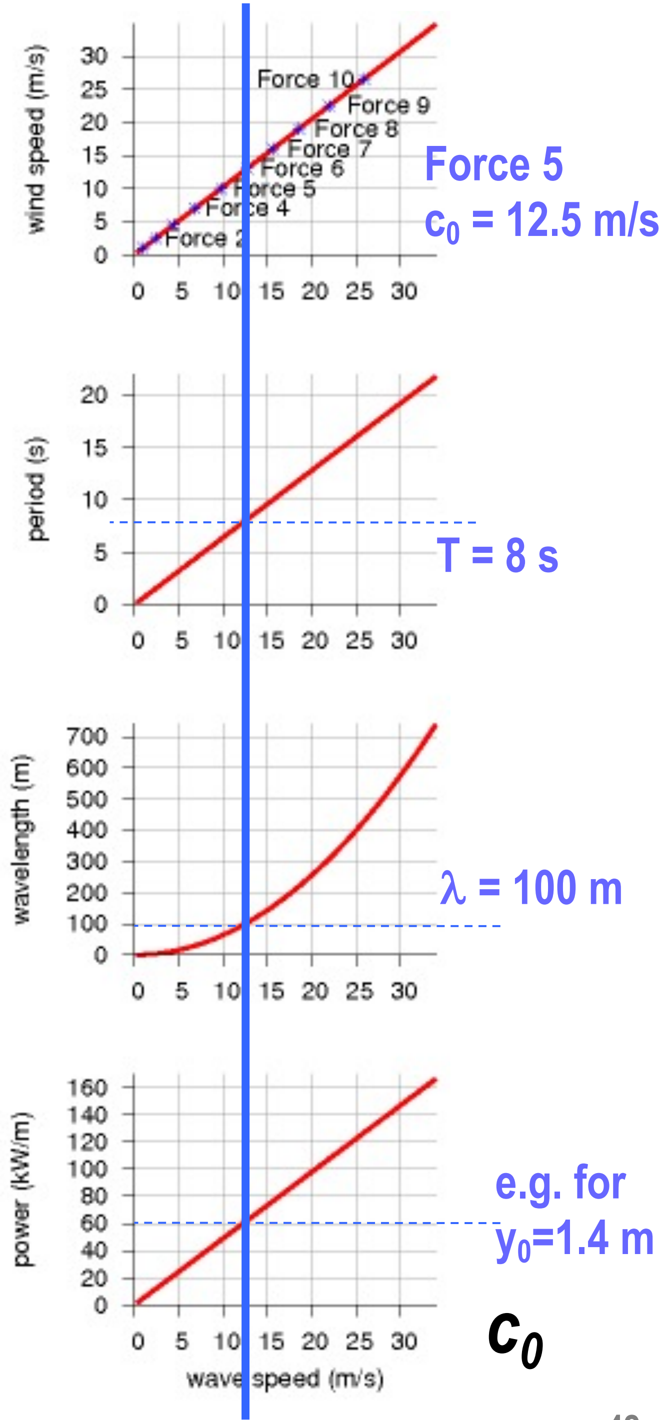
$$P(W/m) = 3064\ y_0^2 \sqrt{\lambda} = 3064\ y_0^2\ \sqrt{0.64\ c_0^2}$$

$$P(kW/m) = 3.064\, y_0^2 \bullet 0.8 c_0 = 2.45\, y_0^2 c_0$$

$\lambda = 100$ m

y_o	P (kW / m)
1 m	30
1.4 m	60
1.7 m	90
2 m	120

The **wavelength** λ (m) and **period** T (s) depend on the **windspeed**.
The **height h** (=2y_0) of the wave depends on the **time** the wind is blowing

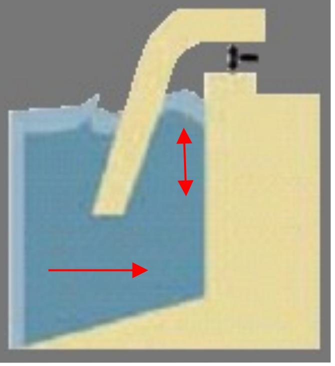


Wave power inspires ingenuity…

The oscillating up-down motion of waves is captured by different approaches, in a rotary or piston motion to drive a generator.

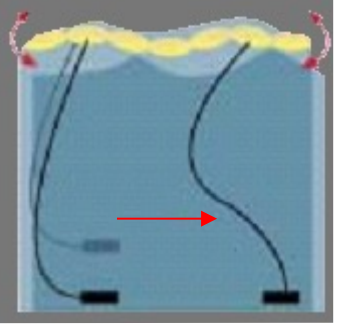
Oscillating Water Column

Waves push air through turbine, then suck it back, as they advance and recede.



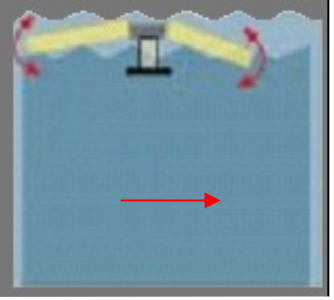
Pelamis

Serpentine devices flex in oncoming waves. Pivoting of segments drives pistons.



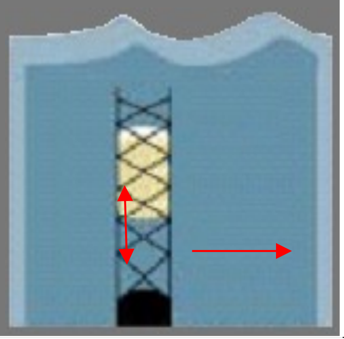
McCabe Wave Pump

Bobbing of outer barges, hinged to central one, stabilized by underwater plate, drives pumps.



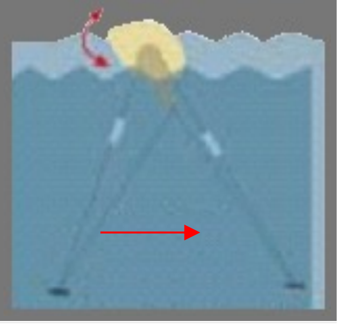
Archimedes Wave Swing

Air tank in fixed, submerged tower rises and falls with passing waves, driving generator.



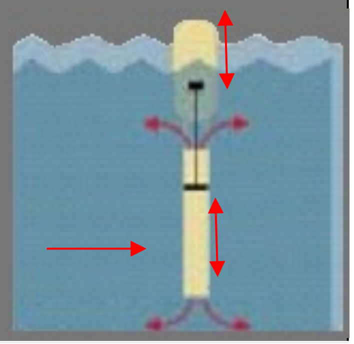
Nodding Duck

Waves push beak of floating device. Its rotation relative to central shaft pumps oil → generator

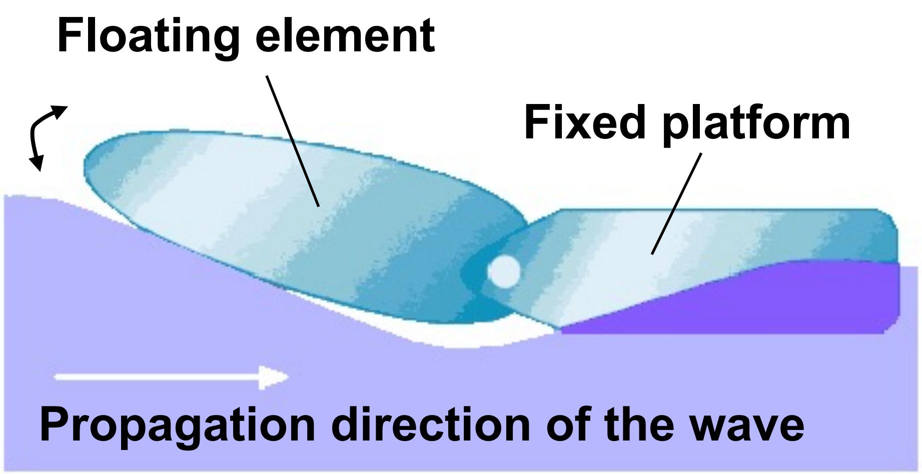


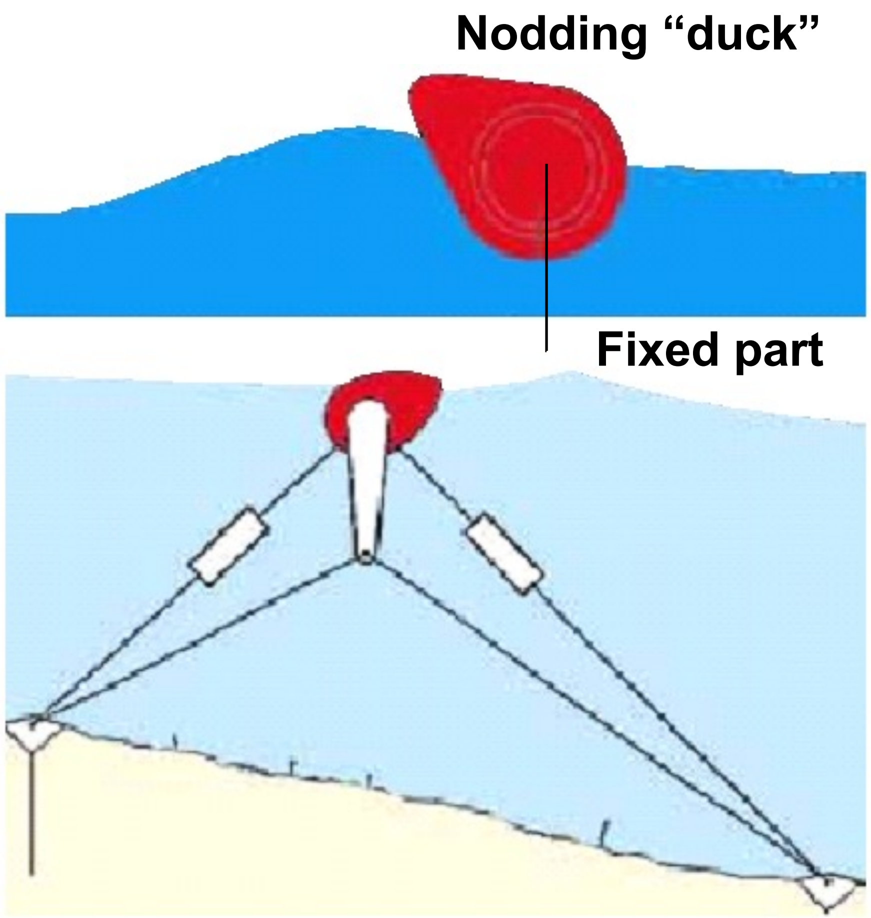
IPS Buoy

Motion of bobbing buoy relative to piston shaft drives generator.



‘Nodding duck’ oscillating device





In shallow water (approaching the shore), the wave energy is lost in sea-bottom friction: from 100 m depth to 15 m depth, 70% is lost.

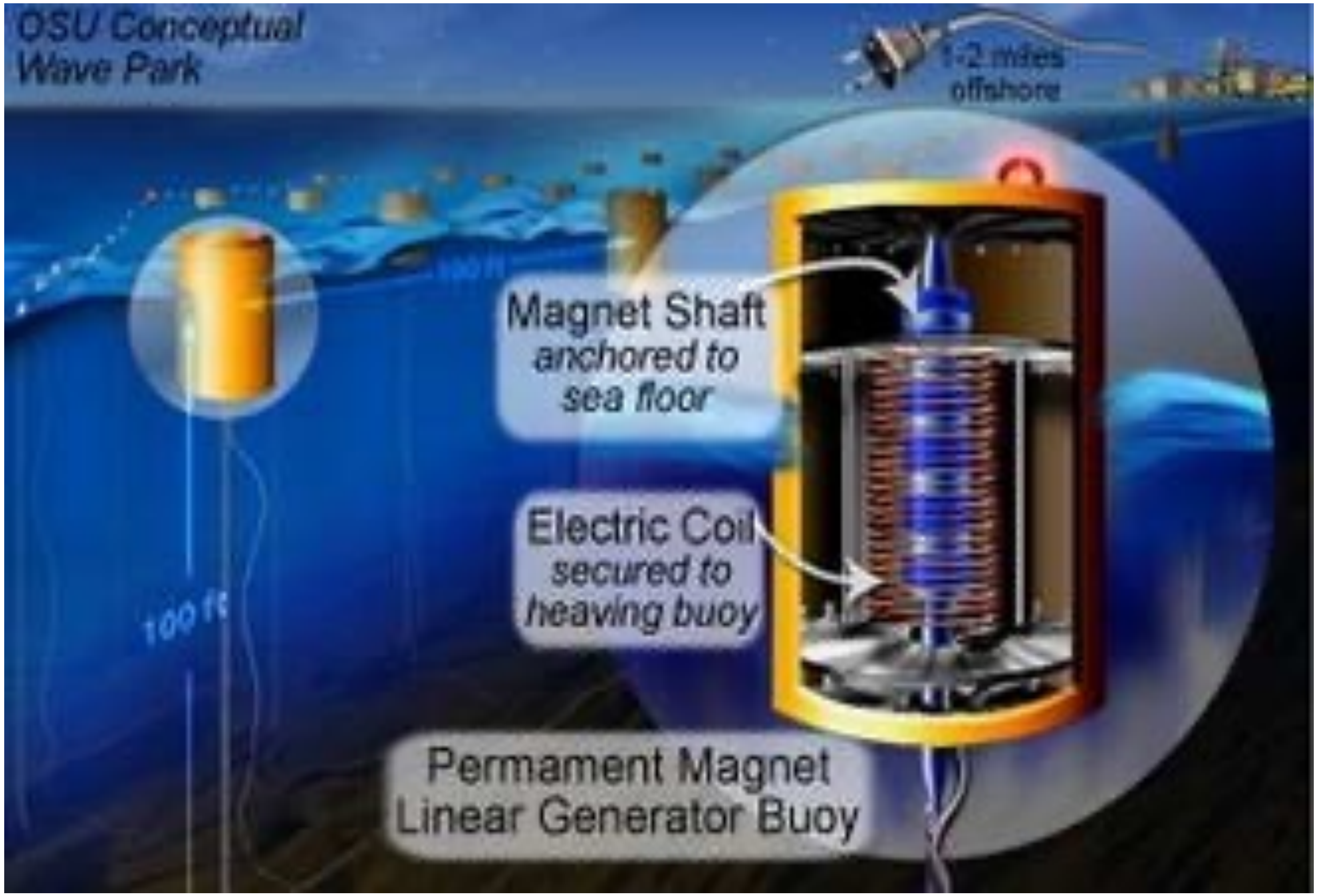
→ a 30 kW/m wave becomes a 10 kW/m wave

Buoy piston oscillating device

http://www.youtube.com/watch?v=90AcxxwoPu0&feature=fvsr

http://www.youtube.com/watch?v=tt_lqFyc6Co&feature=related

In the permanent magnet linear generator buoy, waves cause the coil to move up & down relative to the fixed magnetic shaft. Voltage is induced and electricity generated. A buoy could potentially generate 250 kW power.

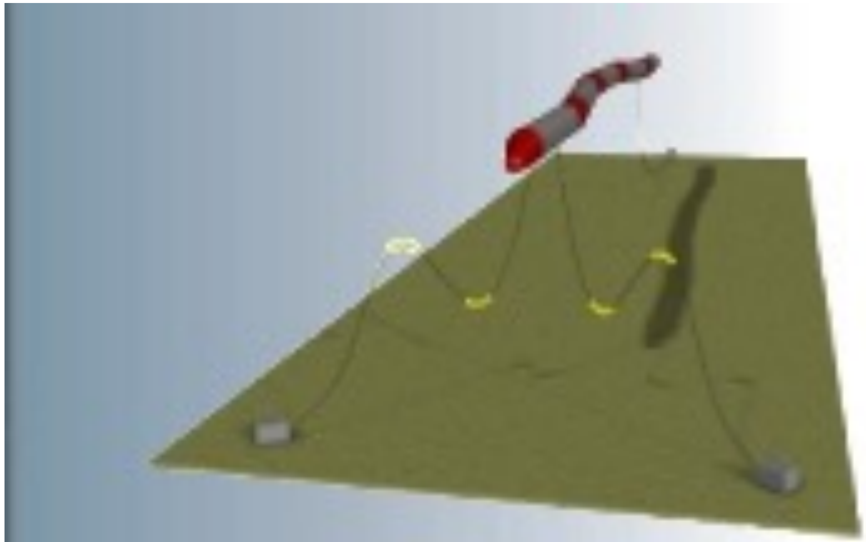


‘Pelamis’ - device

Semi-submerged, articulated structure composed of cylindrical sections linked by hinged joints.

The wave-induced motion of the joints is resisted by hydraulic rams, which pump high-pressure oil through hydraulic motors via smoothing accumulators.

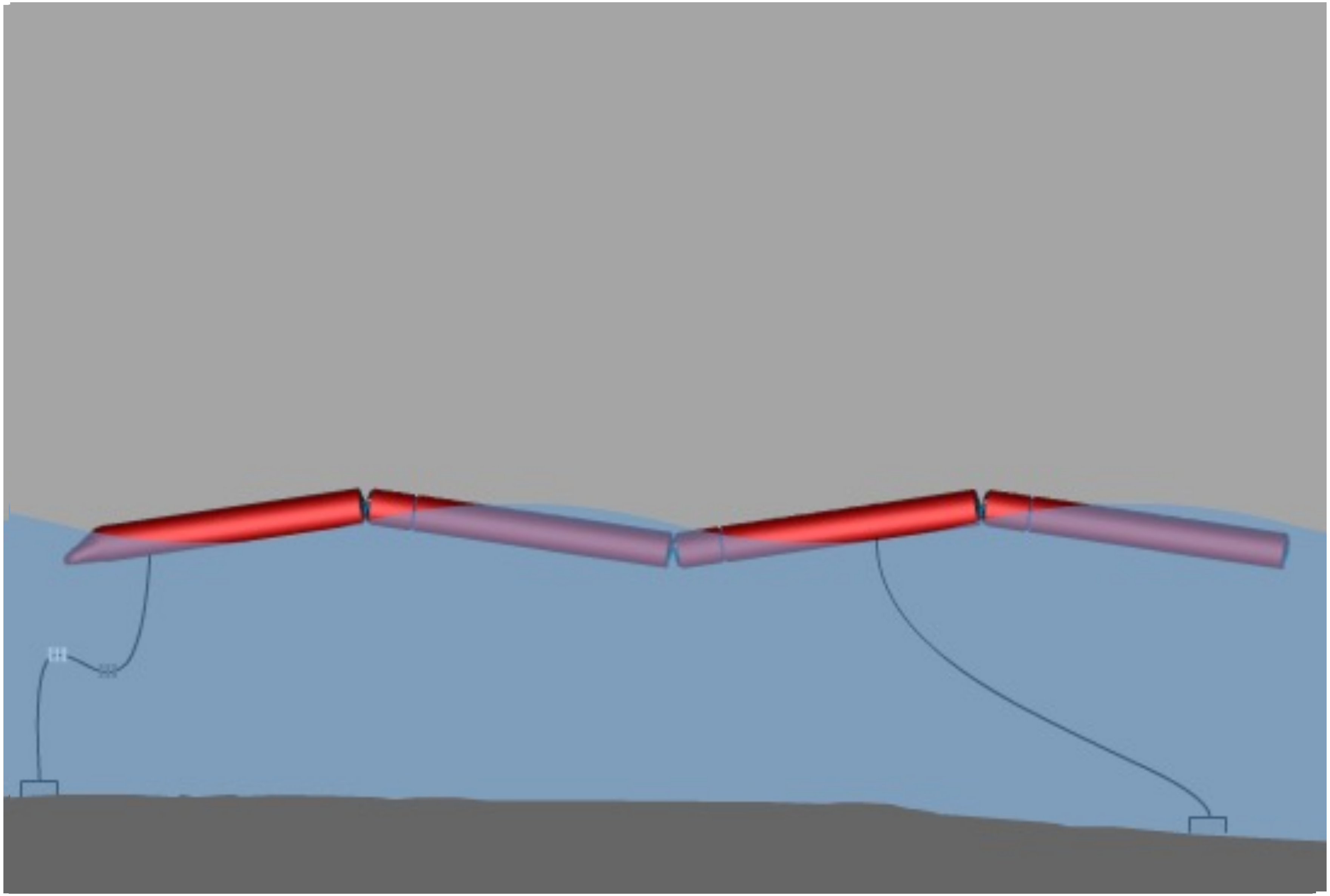
The hydraulic motors drive electrical generators to produce electricity. Power is fed down a single umbilical cable to a junction on the sea bed.



attached ca. 50 m above the sea-bottom

‘Pelamis’-device

http://www.youtube.com/watch?v=F0mzrbfzUpM



Application example

1 Pelamis-snake : **130 m long**; ***3.5m*** diameter D.

750 kW max wave power (i.e. it can take up to 200 kW/m waves!); 350 ton steel (**500 kg/kW!**); *vastly overdimensioned* !

1 km^2 area = 400 m long x **2.5 km wide incoming wave**, 3 rows of 40 Pelamis (120 Pelamis).

Assume **30 kW / m** waves (c_0 = 12.5 m/s, y_0 = 1 m) → 2.5 km wide equals 75 MW_e

1 every 60 m in each row, 1 every 20 m in the wave front, staggered from row 1 to row 3

⇒ *effective wave-front use =* ***3.5m*** */ 20m = 17%*

Incoming power used =

3.5 m * 30 kW/m (1 Pelamis) * 120 = 12.6 MW_e

⇒ **take 70% efficiency** : 8.8 MW_e

⇒ 38.6 GWh_e per year gross electricity, assuming 50% load factor (4380 h/yr) (320 MWh_e/yr for 1)

The same result with same wind (12.5 m/s), at 2500h/yr load), could be achieved with a 18.5 m diameter 130 kW_e wind turbine for 1 Pelamis!

$30\ GW_e$?

Real potential… ?

- assume the UK can ‘block’ 10% of its coast with wave generators …
- the effective wave front use could be ≈ 17%
- assume conversion efficiency ≈ 70%

→ **$0.1 * 0.17 * 0.7 \approx 1.2\%$**

- a net real power of 360 MW_e would result (≈ of the same magnitude as the La Rance tidal scheme **alone(!)**, 240 MW_e)
- again one notices the discrepancy between ‘*potentiality*’ and ‘*reality*’, and the huge installation scales involved.
- wave power is ~marginal, yet interesting for islands ✅