UNIVERSITÀ DI TRENTO

DIPARTIMENTO DI

INGEGNERIA INDUSTRIALE

Tidal power

Renewable Energy Conversion Systems

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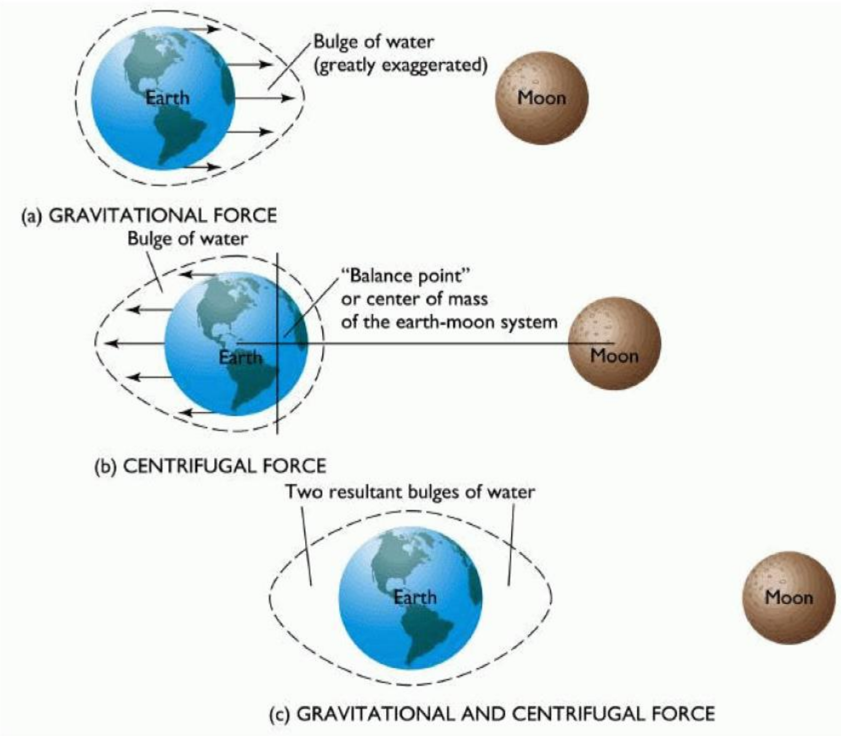
GENERALITIES

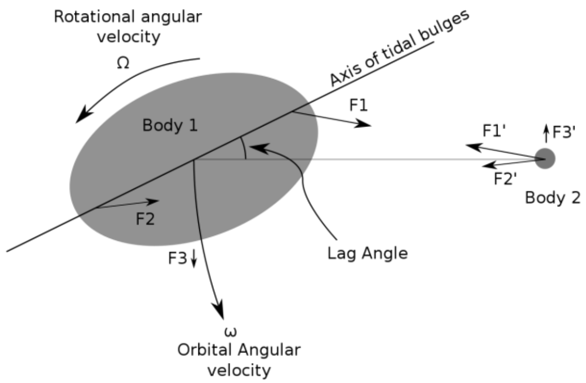
Generalities

Tides are waves generated by the gravitational pull of the Moon and (partly) the Sun, and the Earth rotation, which cause periodic rises (high tide) and falls (low tides) of the sea level.

Approximated schematic:



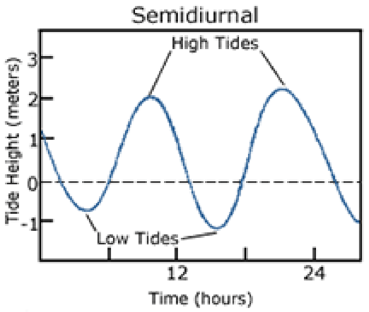
The gravitational attraction of the moon causes a redistribution of the water mass with two tidal bulges on opposite sides: one facing the Moon, and the other on the opposite side. The bulge on the Moon side is due to the Moon attraction force. The bulge at the antipodal position occurs because the gravitational force at this point is weaker than the average gravitational force felt by the Earth as a whole. This weaker force, combined with inertial (centrifugal) forces to which the water is subject due to the Earth rotation, results in an antipodal bulge.

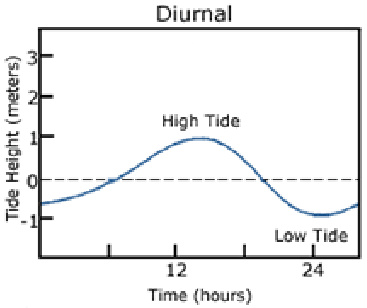


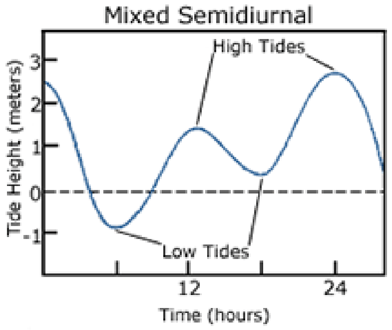
For this reason, tides typically have a <u>periodicity of approx. 12h</u>

Because of the Earth rotation, tidal bulges are not aligned with the Moon-to-Earth axis, but they are dragged «ahead» in the direction of the Earth rotation

Generalities







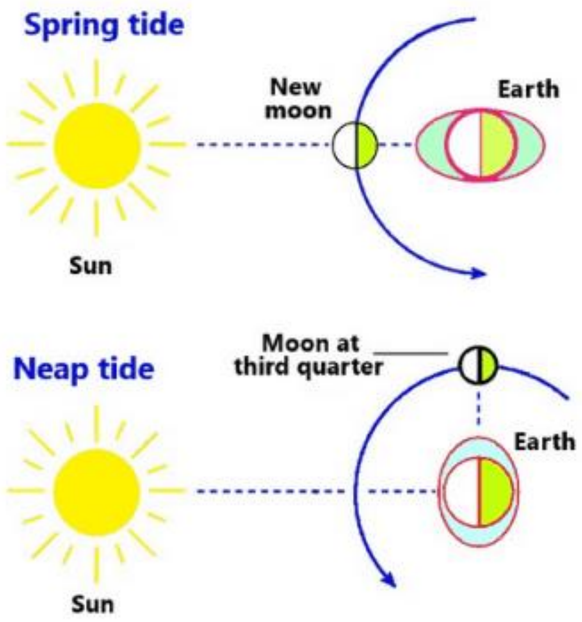
In practice, different areas experiment different tide behaviours, with different periodicity

Semidiurnal tides follow the regular expected behaviour, with 2 high/low tides per day these happens in several areas in Europe, Africa, Australia, North America

Diurnal tides tides have a periodicity of 24 h, with one high and one low tide every lunar day. Such deviation from the regular behaviour is due to local geographical features, the natural frequency of the basin where the tide takes place, complex patterns in the Sun-Moon-Earth gravitational interactions. These happen in areas such as the Gulf of Mexico, the Persian Gulf, and various coastal locations in Southeast Asia.

Mixed semidiurnal tides have intermediate behaviours between the above mentioned mechanisms. An area has a mixed semidiurnal tidal cycle if it experiences two high and two low tides of different size every lunar day. This behaviour, typical along the Pacific coast of North America, is caused mainly by the morphology of the zone and by the angle of the moon in respect to Earth.

Generalities



The Sun also affects tides, though less than the Moon due to its greater distance from Earth.
When the gravitational forces of the Sun and the Moon align, during a full moon or a new moon, we experience higher high tides (**spring tides**), and when they are at right angles to each other, during the first and third quarters of the moon, we experience lower high tides (**neap tides**).

Technically-relevant physical manifestations of tides are
- variations in the water height, which can be used to store water in a basin (potential energy)
- tidal currents, i.e., cyclically-reverting horizontal currents (kinetic energy) due to the periodic rise/fall in the water level

Generalities

Maximum power available from a tidal stream:

$$P = \underbrace{\frac{1}{T}}_{\text{period}} \cdot \underbrace{\rho A H g}_{\text{displaced water weight}} \cdot \underbrace{\frac{H}{2}}_{\text{centre of mass height above minimum tide level}} = \frac{\rho g H^2 A}{2T}$$

where

A is the surface area of a tidal basin
ρ is the density of water
H is the tidal range (height different)
g is the acceleration of gravity
T is the tidal period (e.g., 12 h)

Potential

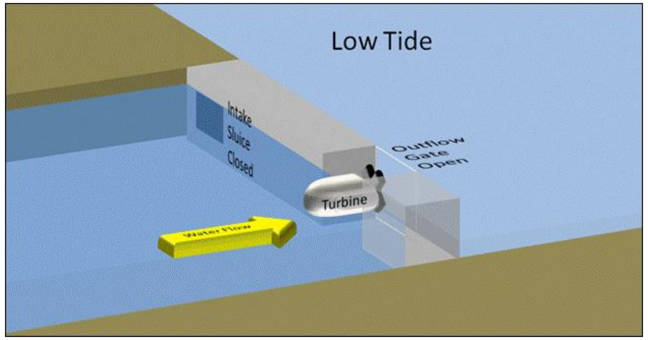
Location	Mean Range (m)	Basin Area (km^2)	Potential Mean Power (MW)	Potential Annual Production (GWh/year)
North America				
Passamaquoddy	5.5	262	1800	15800
Cobscook	5.5	106	722	6330
Bay of Fundy	6.4	83	765	6710
Minas-Cobequid	10.7	777	19900	175000
Amherst Point	10.7	10	256	2250
Shepody	9.8	117	520	22100
Cumberland	10.1	73	1680	14700
Petitcodiac	10.7	31	794	6960
Memramcook	10.7	23	590	5170
South America				
San Jose, Argentina	5.9	750	5870	51500
United Kingdom				
Severn	9.8	70	1680	15000
Mersey	6.5	7	130	1300
Solway Firth	5.5	60	1200	10000
Thames	4.2	40	230	1400
France				
Aber-Benoit	5.2	2.9	18	158
Aber-Wrac'h	5	1.1	6	53
Arguenon	8.4	28	446	3910
Frenaye	7.4	12	148	1300
La Rance	8.4	22	349	3060
Rotheneuf	8	1.1	16	140
Mont St Michel	8.4	610	9700	85100
Somme	6.5	49	466	4090

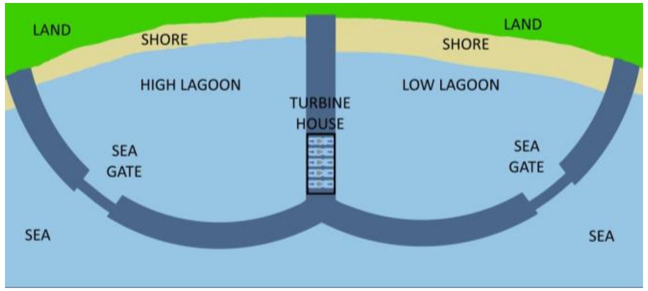
Location	Mean Range (m)	Basin Area (km^2)	Potential Mean Power (MW)	Potential Annual Production (GWh/year)
Ireland				
Strangford Lough	3.6	125	350	3070
Russia				
Kislaya	2.4	2	2	22
Lumbouskii Bay	4.2	70	277	2430
White Sea	5.65	2000	14400	126000
Mezen Estuary	6.6	140	370	12000
Australia				
Kimberley	6.4	600	630	5600
China				
Baishakou	2.4	No data	No data	No data
Jiangxia	7.1	2	No data	No data
Xinfuyang	4.5	No data	No data	No data

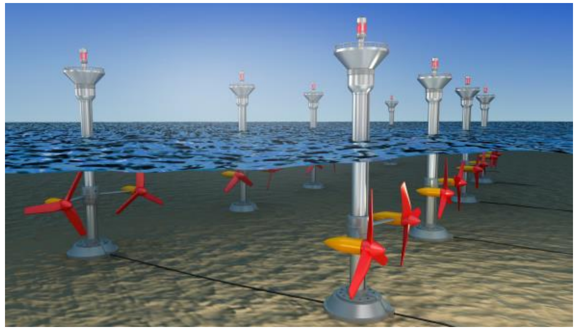
Technologies

There exist two main methods to harness tidal currents:

- **Tidal stream turbines**: machines similar to wind turbines, operating in water, put in rotation by tidal currents. Similar to wind power
- **Tidal barrages/Tidal lagoons**: semi-permeable barrages built across estuaries (either extending across the entire estuary, or built as self-contained structures) with high tidal range. Tidal energy is extracted by these methods with flood generation, ebb generation or a combination of them.

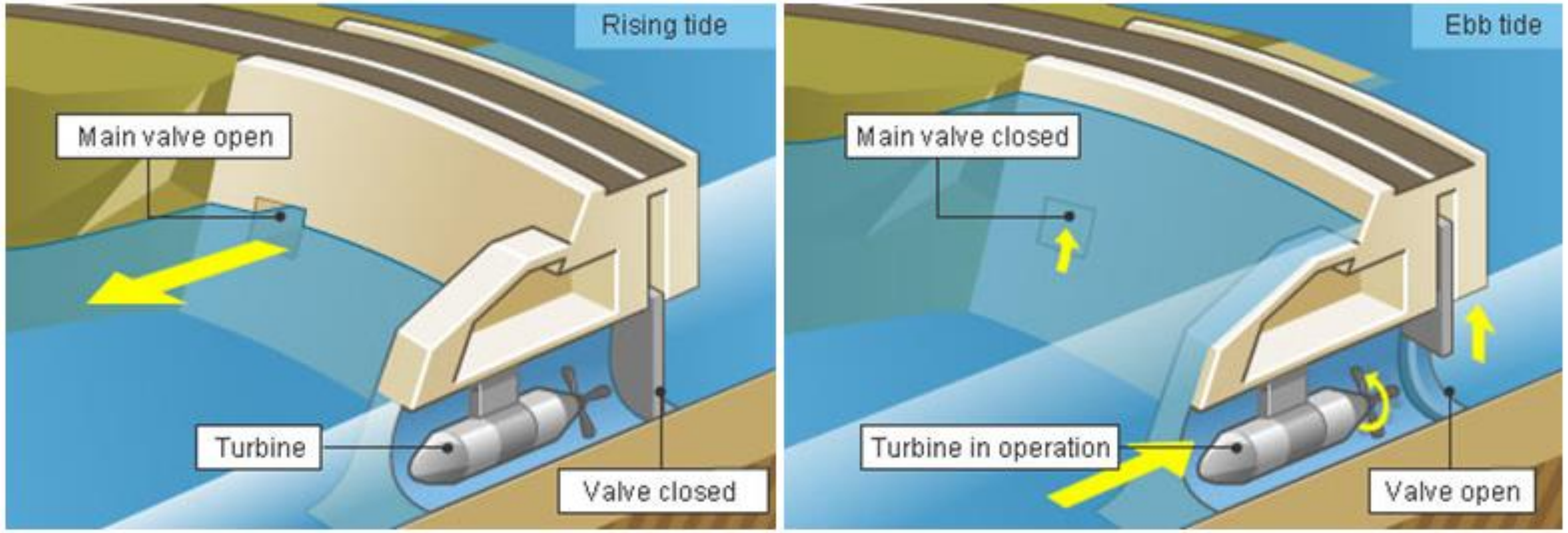






TIDAL BARRAGES

Definition



The main parameter quantifying energy production in a tidal barrier is the tidal range. Tidal ranges increase towards coasts, and particularly in estuaries, because of seabed shelving, the funneling of water and, in some cases, resonance effects. Most tidal barrages are built across estuaries that experience high tidal range. This plants are similar to hydroelectric plants, which rely on hydroelectric turbines to harvest the energy stored within a basin.

The tidal barrage shown in the figure represents a simple *ebb generation* system with two gates: one to allow water in and out of the basin and the other gate is used instead to push water through turbines to produce energy.

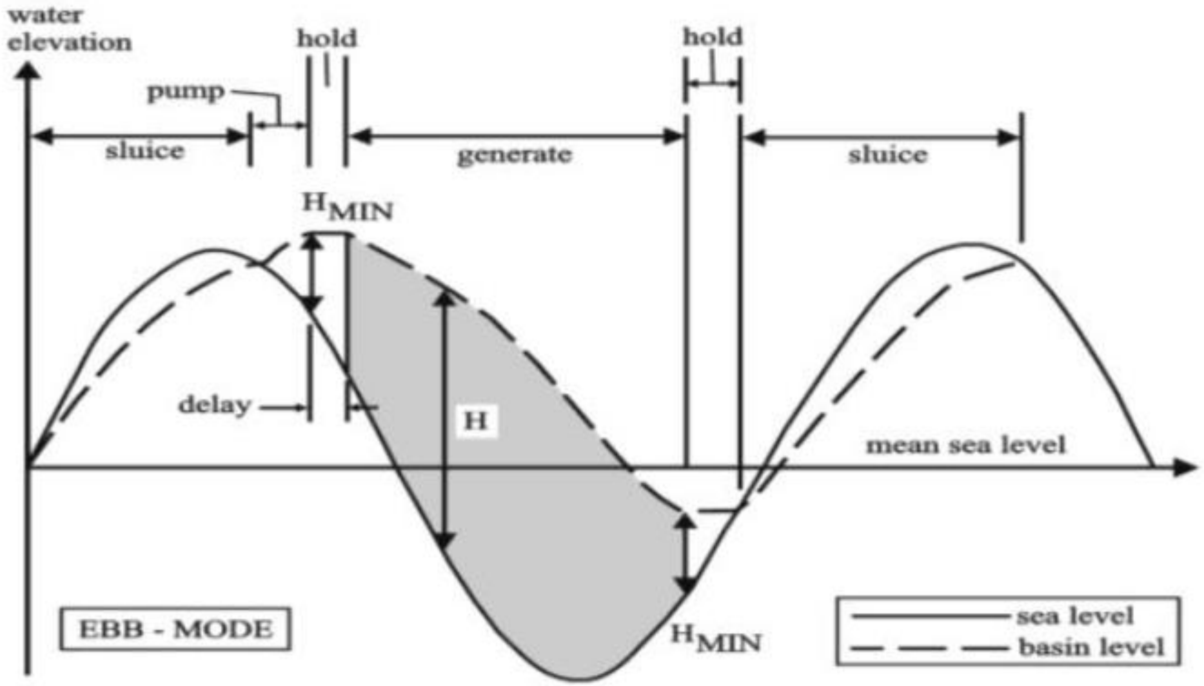
Working modes of tidal barrages

• **Ebb generation**. During *flood tide*, when water moves inland, the basin is filled with water that is then trapped by sealing the gates. When *ebb tide* begins, the water moves seaward except for that closed inside the basin. When the water level outside the basin becomes sufficiently lower than the basin level, the turbine gates are opened and the water flows out of the basin through the turbines, due to the accumulated height difference.
These plants can be used for medium-term energy storage, by using the turbine in reverse (e.g., during the night, when power demand is low and excess power is produced by other sources) to pump water into the basin.

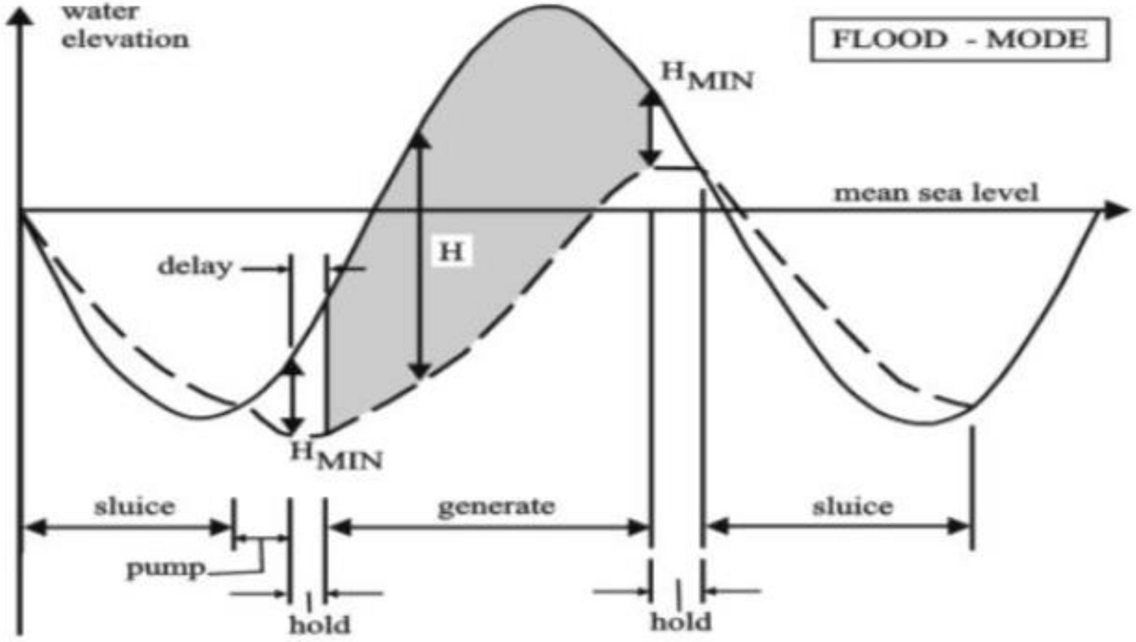
• **Flood generation**. It works in reverse compared to ebb generation. In fact, at high tide the gates are already closed and when a sufficient height is reached outside the basin, the gates are opened to permit the water to flood into the basin. The generation process is the same described above, with water flowing in the opposite direction (turbines are mounted in the opposite direction)

• **Two-way generation**. Both flood and ebb phases of the tides are used to produce electricity. The sluice gates and turbines remain sealed close until the end of the flood cycle, when they are opened allowing water to flow inside the basin. When water reaches an adequate level, the sluice gates are closed again and reopened at the end of ebb cycle to move water outside the basin.
This process allows to produce electricity each time the water moves inside or outside the basin and, therefore, it is advantageous because of reduction of non-generation period.

Working modes of tidal barrages

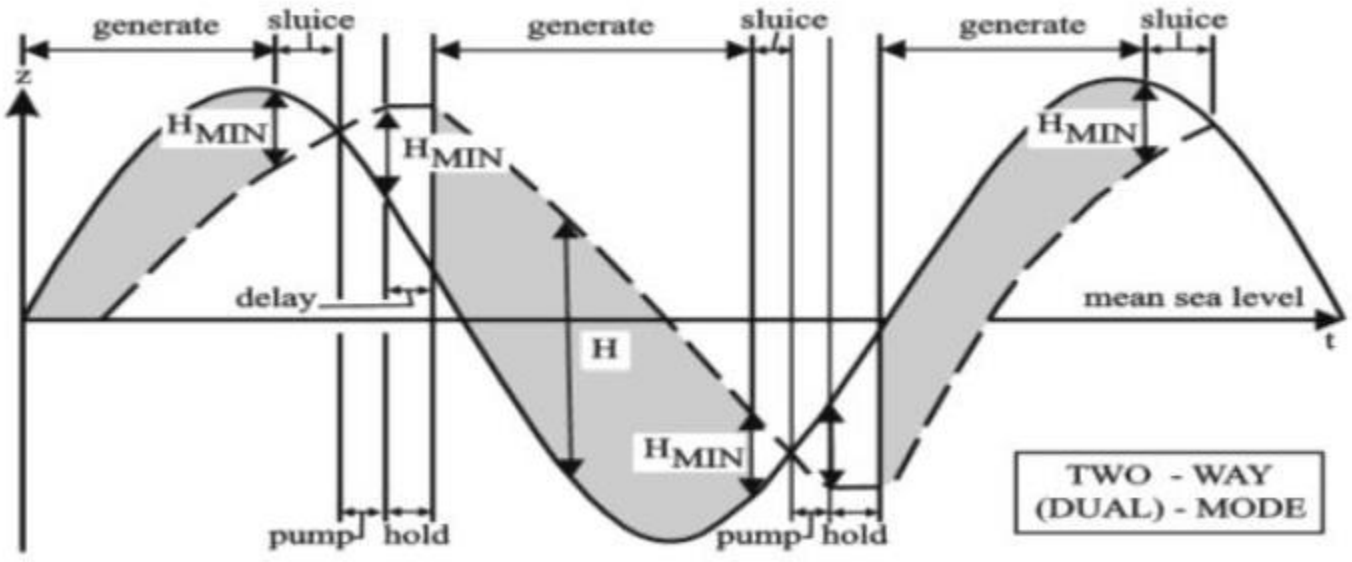


Ebb generation



Flood generation

Working modes of tidal barrages



Two-way generation

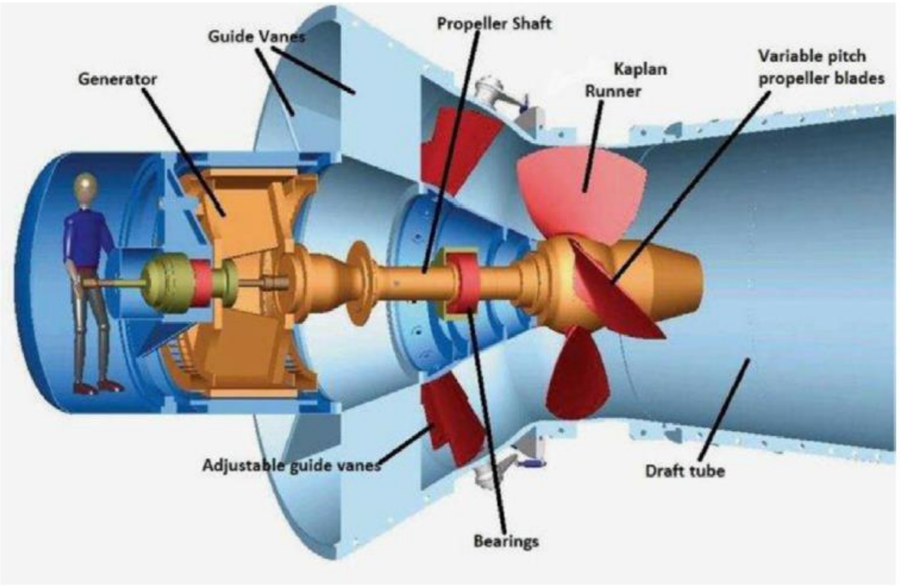
Turbines for tidal barrages

The most common turbine type for tidal barrages are **bulb turbines**, a special version of the Kaplan turbine installed within a delivery tube.

Main components:

- guide vanes (inlet)
- Runner (rotor)
- Draft tube

Bulb turbines can reach efficiencies as high as 90% over a broad range of flow/head values, thanks to adjustable propeller blades, though the efficiency significantly drops down if the turbine is operated in reverse



Speed triangles @ the blackboard

Examples of tidal barrage projects

To date, tidal barrage projects are few and geographically scattered. The leading countries in terms of operational output are France and South Korea.

Table 1
Existing Tidal Power Plants in the World.

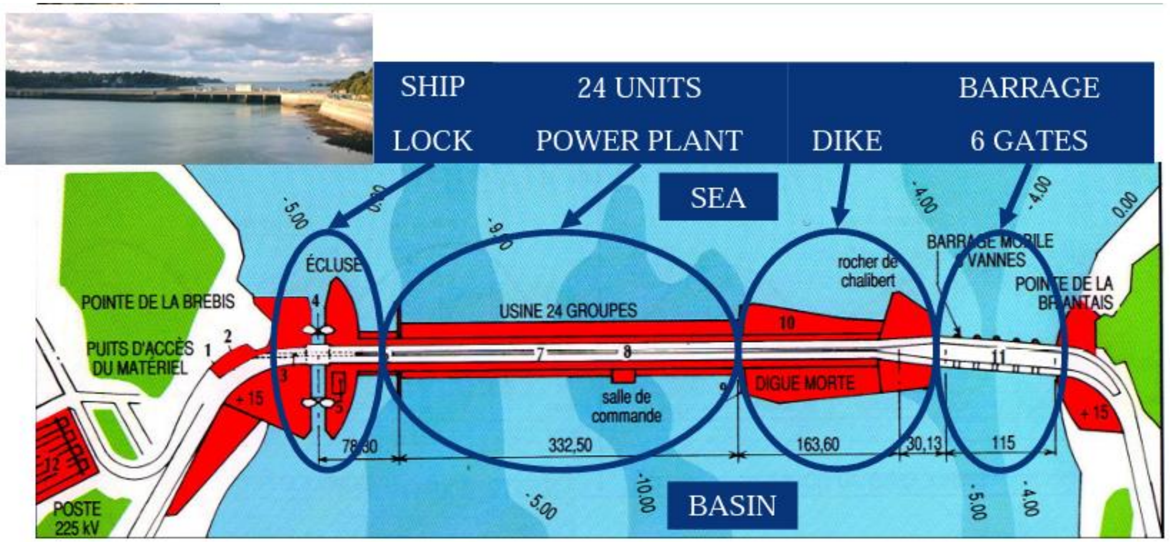
Station Name	*La Rance*	*Jiangxia*	*Annapolis*	*Sihwa*
Country	France	China	Canada	South Korea
Capacity (MW)	240	3.9	20	254
Annual Output (GWh)	540	6.5	30	553
Year	1966	1980	1981	2015
Turbine Number	24	6	1	10
Turbine Type	Bulb	Bulb	Rim	Bulb
Basin Area (km^2)	22	1.4	15	56
Mean Tide/m	8.5	5.1	6.4	5.6

La Rance barrage (FR)

Located near to St.Malo, France, La Rance tidal barrage was the first tidal project to become operational (1966-67). Cofferdams were used for the construction, which involved creating circular dams and draining the water from within the basin. A 720 m long barrage links the two sides of the river, capturing a 22 km^2 area of water in the process. It also doubles up as a road link across the river.

Working cycle: Ebb or two-way
Turbine: 24 x Kaplan bulbs, used also in pumping mode
Generators: supplied rotor synchronous machines (sealed)

Property	Value
barrage length	750 m
power plant length	332.5 m
tidal basin	22.5 km^2
max tidal range	13 m
power peak	240 MW
average power	54 MW
capacity factor	24%
annual power	600 GWh
number of turbines	24
water flow in the estuary	20000 m^3/s
number of gates	6
gates height	10 m
gates length	15 m



TIDAL TURBINES

Overview

Tidal stream turbines can be used without the presence of an estuary, a barrage or a particular morphology of the coastline, thus bearing a much larger potential for penetration/upscaling compared to barrages.
To date, tidal turbines are at a *pre-commercial* stage, with an installed capacity of roughly 30 MW in Europe.
At European level, locations with constant current speeds above 0.5m/s could provide an annual energy production of 48TWh/yr, with most of the resource concentrated around the British Isles and the English Channel.

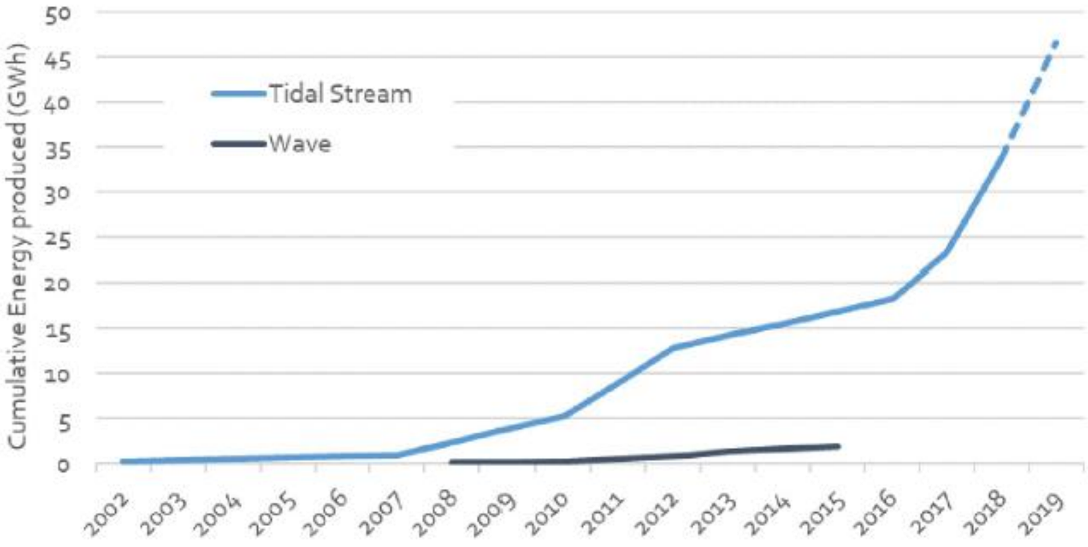


Figure 2.10: Tidal stream cumulative energy produced 2002-2019 [12].

Overview

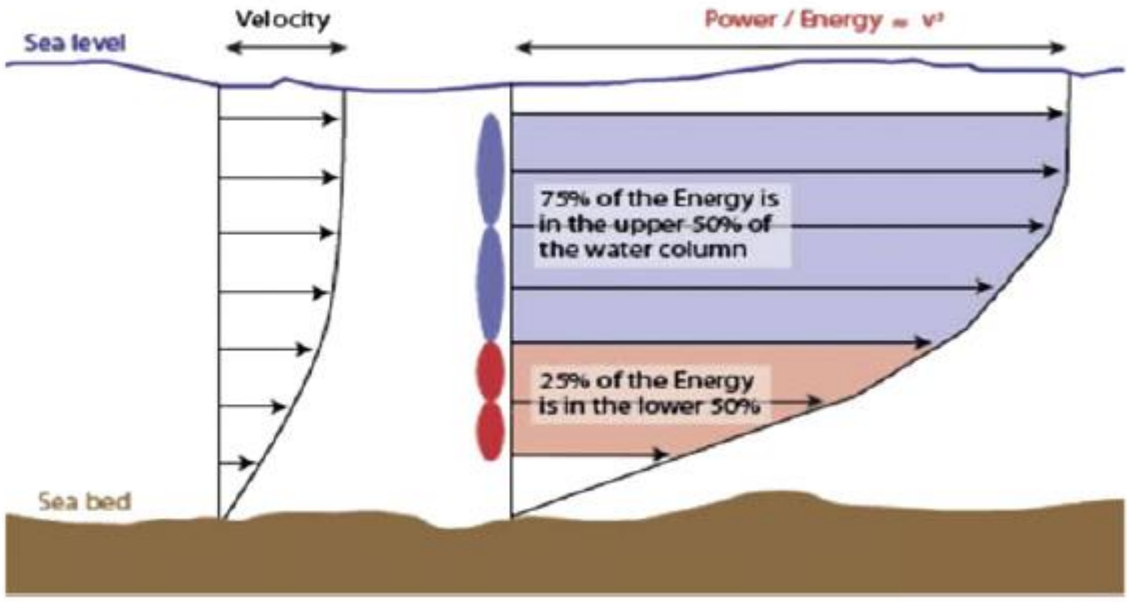
Tidal vs Wind Turbines

Tidal and wind turbines are functionally and morphologically similar, with some major differences:

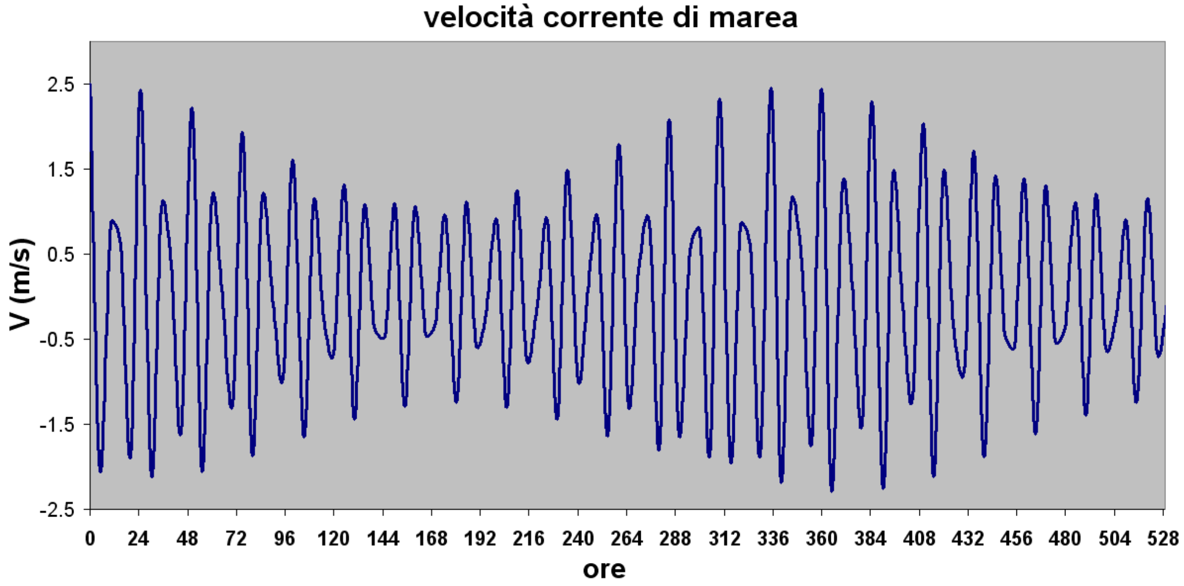
- Water is >800 times denser than air. It carries more energy, and creates higher structural loads on the turbine blades and structure
- Tidal currents' typical speed (0.5-3 m/s) is lower than wind speed (10-15 m/s)
- Water viscosity is larger than air's (10^{-3} Pa·s vs 10^{-5} Pa·s), leading to lower hydrodynamic efficiency.
- Tidal stream turbines should be able to operate in both directions (as the water flow reverts) to produce electricity during both ebb and flood phases
- Turbine blades for tidal application are shorter, because of the higher forces they are subject to, which result in larger bending moments
- The operating ranges of tidal turbines are less variable than those of wind turbines, as tidal currents tend to be more regular and periodic.
- Tidal turbines are subject to cavitation and corrosion

Tidal current speed

A turbine with small rotor, placed just below the surface of the water, is subject to a rather uniform speed profile; moreover, the water speed close to surface is much higher than close to seabed.



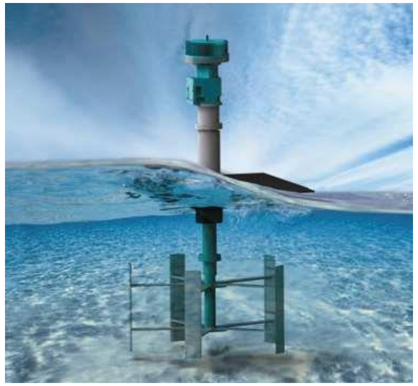
Velocity and power distribution through water column



Tidal turbine technologies

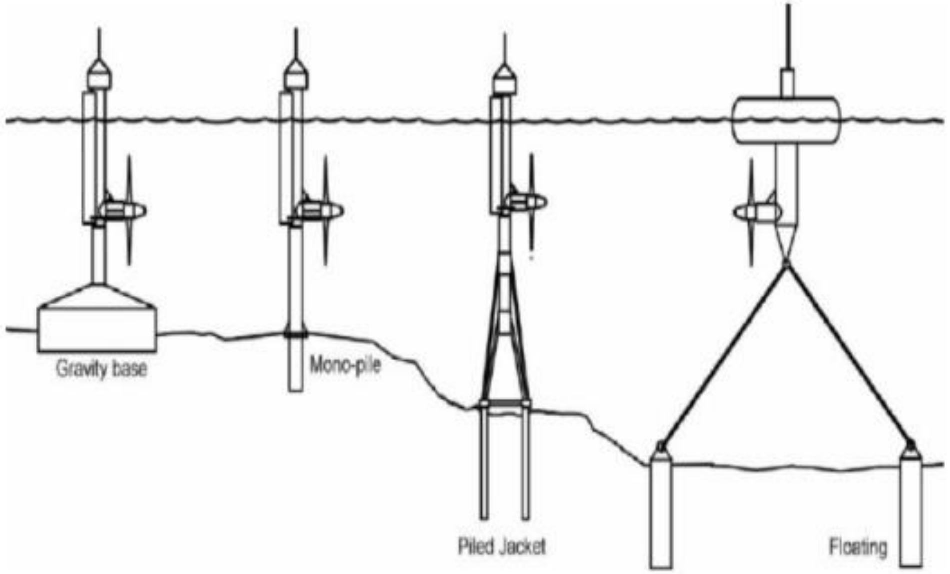
Turbine types

- Horizontal axis
- Vertical axis



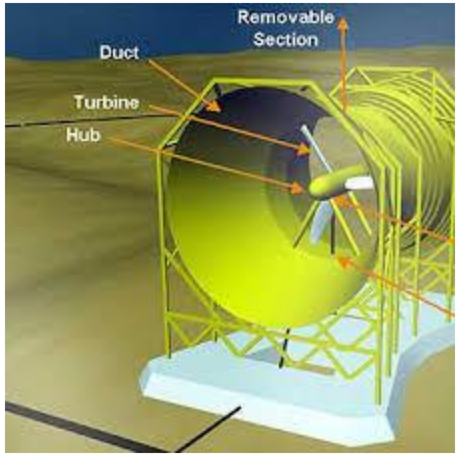
Vertical axis turbines are intrinsically adaptable to direction changes in the current, whereas horizontal axis turbines require either yaw adjustment mechanism, or the ability to revert the rotor speed in the presence of currents with opposite speed direction.

Mooring



Ducted tidal turbines

Several horizontal axis tidal turbine projects foresee the presence of a flow enhancer, namely a Venturi tube, surrounding the rotor. The role of the enhancer is to increase the fluid stream speed at the rotor and, hence, the maximum power that can be extracted.
In the presence of a flow enhancer, a turbine can convert a maximum amount of power that is above the Betz limit (in terms of extractable power per unit rotor area)
Flow enhancers are popular in tidal turbines (more than in wind turbines) because:
- this partly counterbalances the efficiency loss due to flow inversion
- a technological standard does not exist yet, leaving more room for technological experimentation
- the duct shelters the rotor from interaction with the external environment

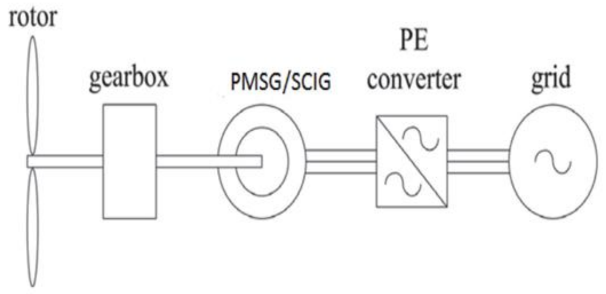


Cavitation

Cavitation is a technically relevant phenomenon in liquid-driven fluid machinery (hydraulic turbines, hydraulic actuators etc) that involves the local formation of vapor bubbles in a liquid. This happens when the fluid pressure goes below the vapor pressure (i.e., the pressure exerted by a vapor that finds itself at the same temperature as the liquid, at equilibrium).
In hydraulic turbines, cavitation happens as the fluid pressure decreases when the flow crosses the turbine, potentially leading to vapor bubbles formation. Impact of the bubbles with the blades can cause the bubbles' recompression and sudden collapse, which generates shock waves that are likely to damage the machine components.

Generators

Similar to wind turbines, tidal turbines’ coupling with generators can either make use of gearbox or be direct-drive (using low-speed multi-pole generators).
Employed generators are typically squirrel cage induction machines or permanent magnet synchronous machines (PMSG). Although most manufacturers use conventional air gap generators, because the system works underwater flooded generators (with water gap) have been proposed too, which make use of stator/rotor cans to protect the windings/magnets from water, while allowing water in the gap.



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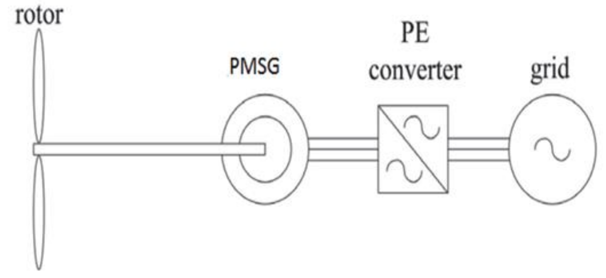

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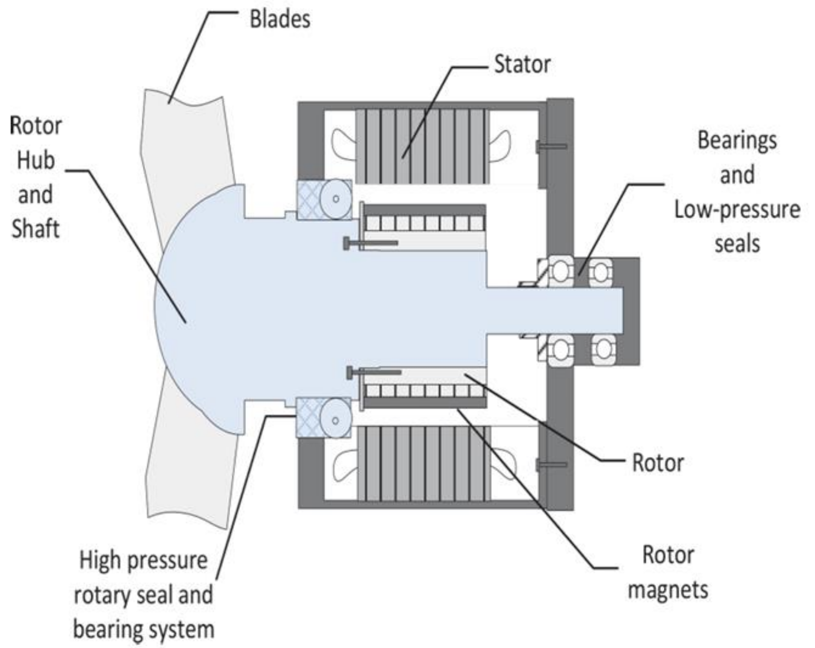

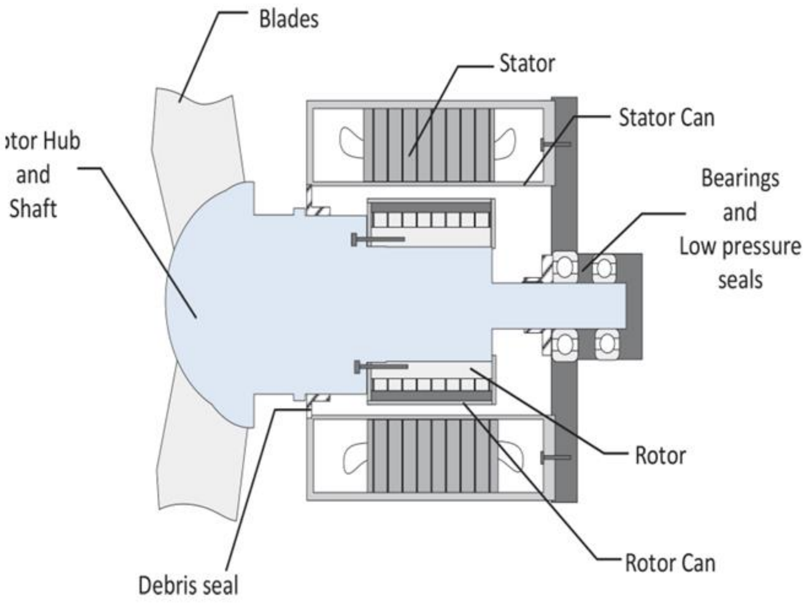

MeyGen project

MeyGen is a tidal stream energy array of 1.5 MW tidal turbines, located in the Pentland Firth, an offshore site near Scotland’s northernmost coast. At its first phase, it had four tidal turbines to produce a total power of 6 MW. The project is in construction and has the goal to reach about 398 MW of installed tidal stream energy capacity, in roughly 25 years. Current speeds at the deployment site reach values as high as 1-4.5 m/s.

Turbines: Horizontal axis turbines with rotor diameter of 18 m, variable speed, reach rated power (1.5 MW) at current speeds of 3 m/s.
Foundation: Gravity-based