19-Tidal Systems

ECEGR 4530

Renewable Energy Systems

Overview

- Introduction
- State of the Tidal Industry
- Tidal Resource
- Tidal Range Operation
- Environmental Concerns
- Tidal Stream Generation

Introduction

- Tidal energy is one of three sources of renewable energy (solar, geothermal)
- Large-scale electricity from tidal began in 1966
- Two types of tidal schemes:
  - Tidal Range (potential energy)
  - Tidal Stream (kinetic energy)

Tidal Energy Industry

- Electricity generation from tidal sources is not yet commercially viable
- A small number of tidal plants exist, mostly pilot or proof-of-concept
  - Notably:
    - Rance (France) 240 MW
    - Fundy Bay (Canada) 20 MW
- Estimated potential (shallow water) ~1000 GW
- Several promising locations in Pacific Northwest

Is it renewable?

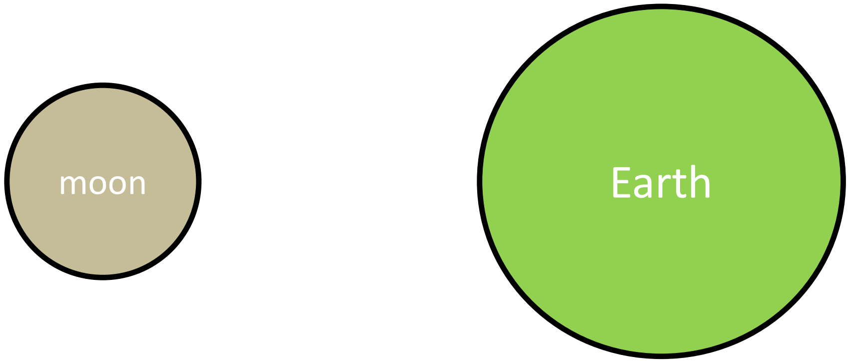
- Energy extracted from tides results in the gradual slowing down of the rotation of the earth
- Earth's rotation is naturally slowing due to tidal action
- Added deceleration under most reasonable scenarios is no more than one day per 2000 years—not a concern

Tidal Resource

- Tides are caused primarily by the gravitational attraction of the Earth-Moon system
- Tides are distinct from waves (which are caused by wind)
- "Tidal waves" are neither caused by tides, nor waves, but earthquakes
- Coastal areas experience approximately two high tides, and two low tides per day

Earth-Moon System

Moon orbits the earth every 27.323 days (sidereal month).
The orbit is elliptical: apogee 405,000km; perigee: 362,000 km
Moon is “tidally locked” so that the same hemisphere of the moon is always facing the Earth

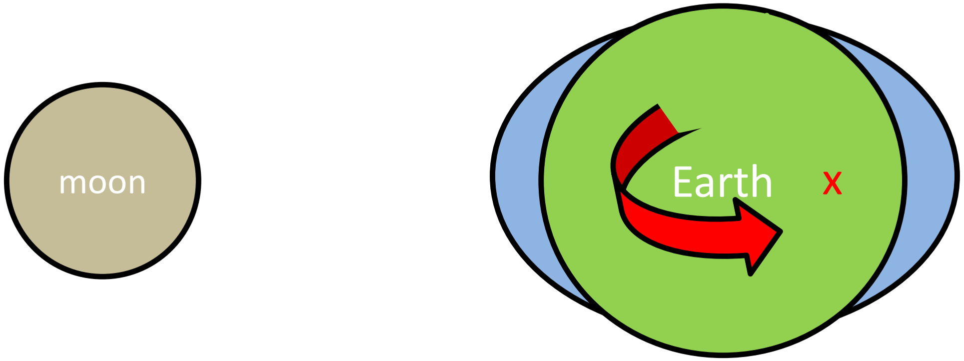


Not to scale

That the moon seems larger when it is on the horizon is in fact an optical illusion

Tidal Resource

- Water bulges on opposite sides of the Earth
- As the Earth spins, it rotates through these bulges
- A coastal area experiences high tide when it is in a bulge, a low tide when it is midway between the bulges

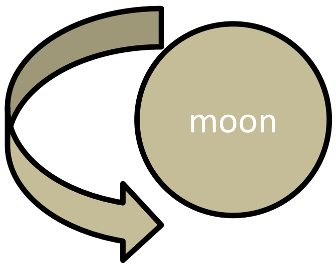


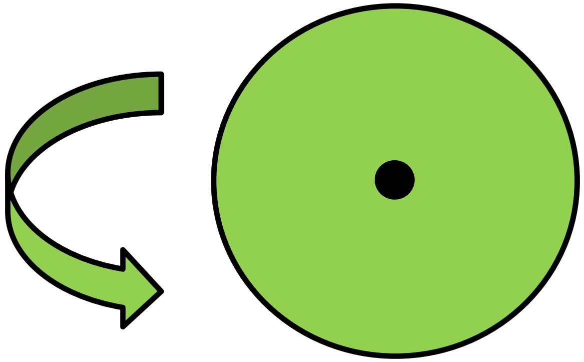
The location "x" will experience high tide when it passes through the bulge of water

Tidal Resource

- Two mechanisms cause the bulges
  - Centrifugal effect
  - Gravity from the Moon
- Centrifugal force and gravitational force maintain the separation of the Earth and Moon
- The height of the tides depends on many features, including local geographic features, ocean dynamics, etc., which we ignore in this formulation

Earth-Moon System





Looking down on the North Pole

The Earth and Moon orbit the sun in the same direction and also rotate in the same direction.
Note: although only one side of the Moon faces the Earth, the Moon it does rotate as seen by a distant observer. There is no "dark side" of the Moon

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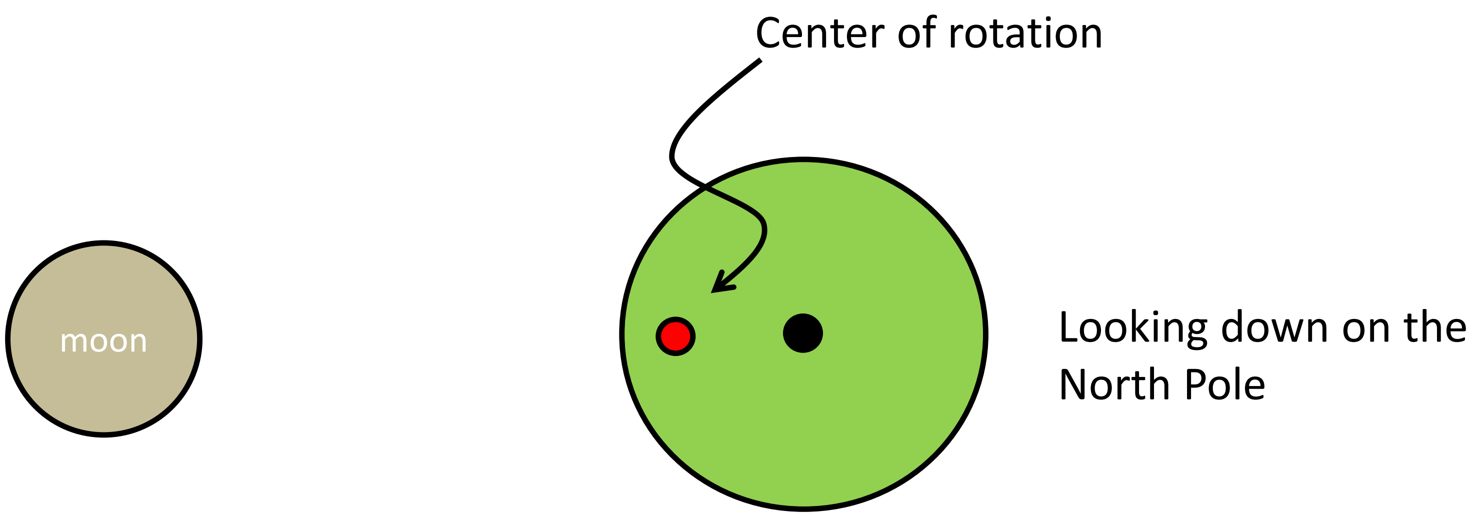
Earth-Moon System



The center of rotation of the earth-moon system is inside the Earth (the center of rotation depends on the mass of the Earth and Moon and their separation).

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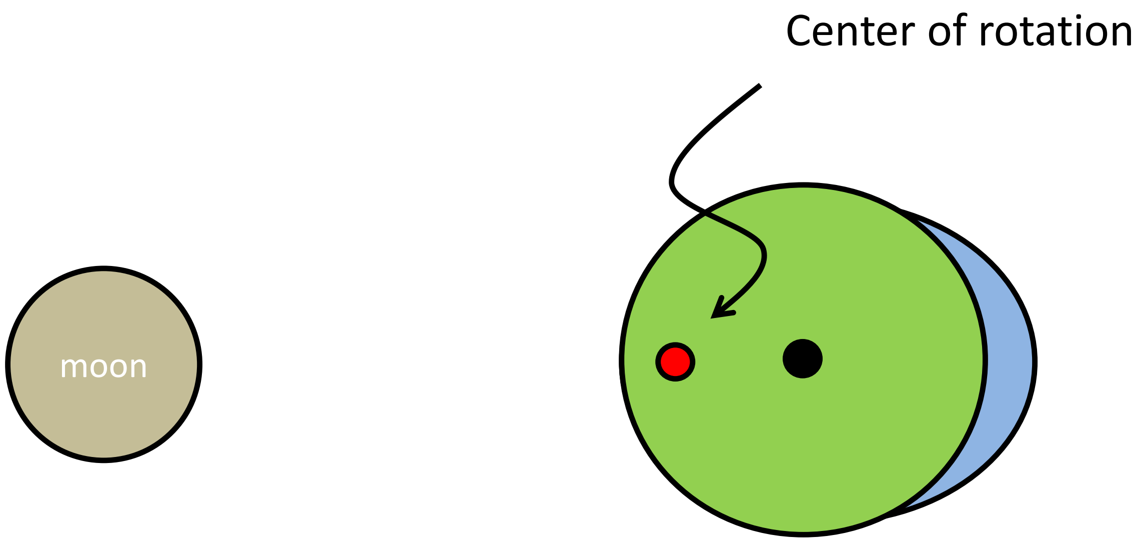
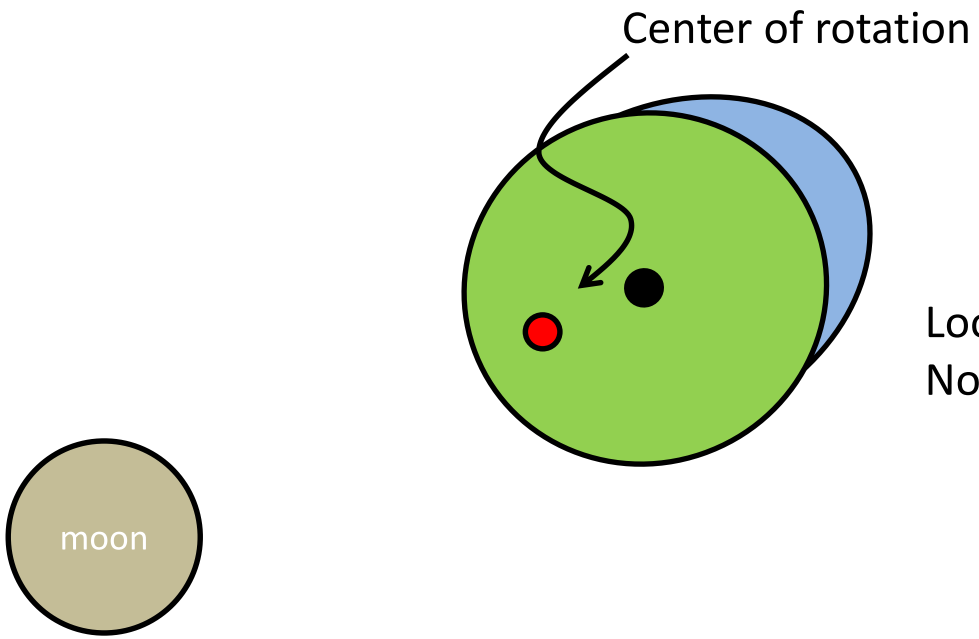
Earth-Moon System



As the Earth rotates around the center of rotation,
It experiences an outward centrifugal force that causes
the moveable liquid to bulge on the far side from the moon

Not to scale

Earth-Moon System



Looking down on the North Pole

The water whips around to the far side of the Earth.

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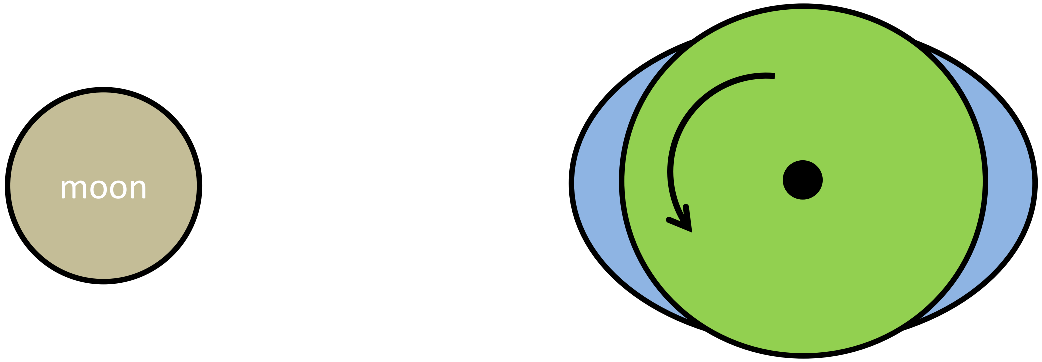
Earth-Moon System



The moon's gravity exerts a force on the Earth, causing the water to bulge on the near side.

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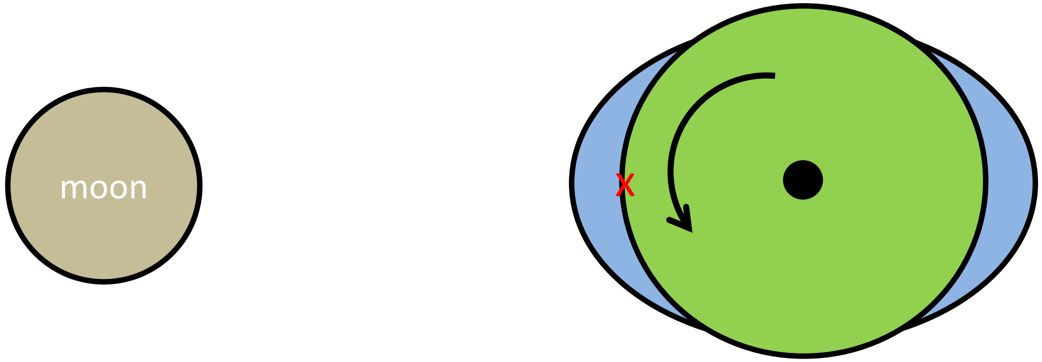
Earth-Moon System



Let “X” be at the position shown at 12:00. The location is experiencing a high tide.

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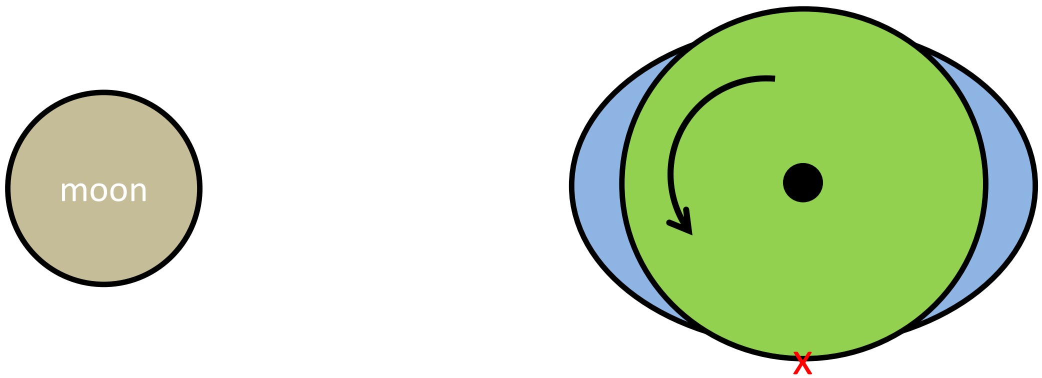
Earth-Moon System



Due to the Earth's rotation, at 18:00, it will be as shown.
Location X will experience a low tide.

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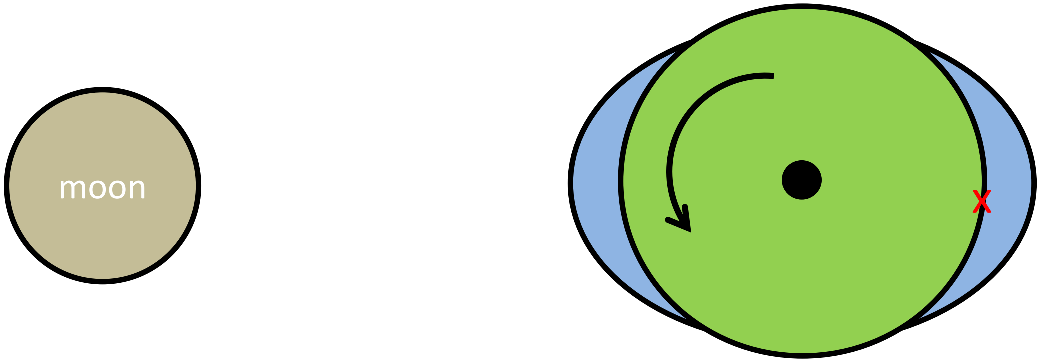
Earth-Moon System

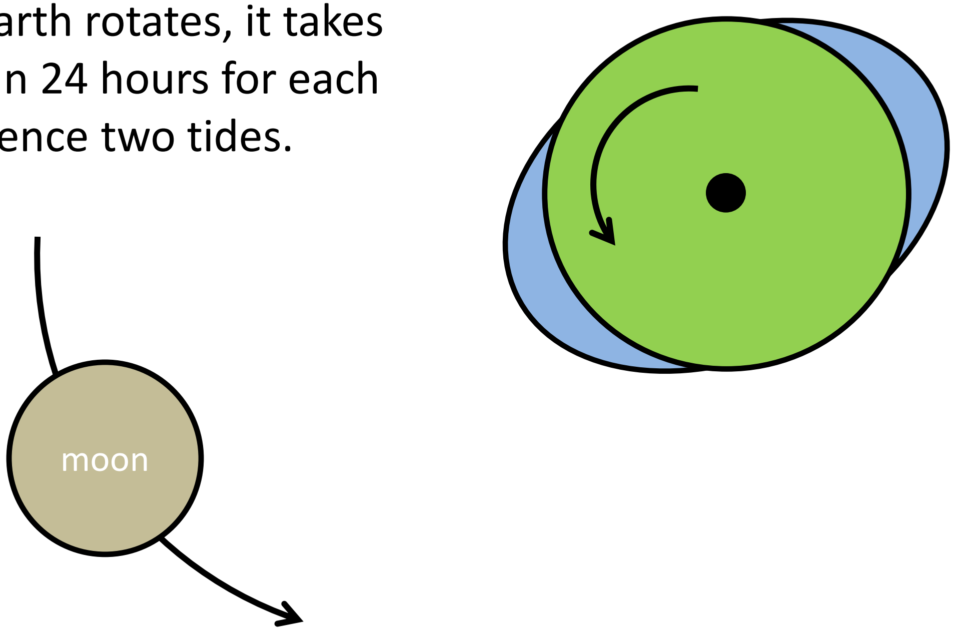


At 0:00 it will experience another high tide (as shown), and at 6:00 it will experience a low tide.
However, we've ignored the orbit of the moon.

Not to scale

Earth-Moon System

As the moon orbits, the bulges follow. Since the moon orbits in the same direction as the Earth rotates, it takes slightly longer than 24 hours for each location to experience two tides.



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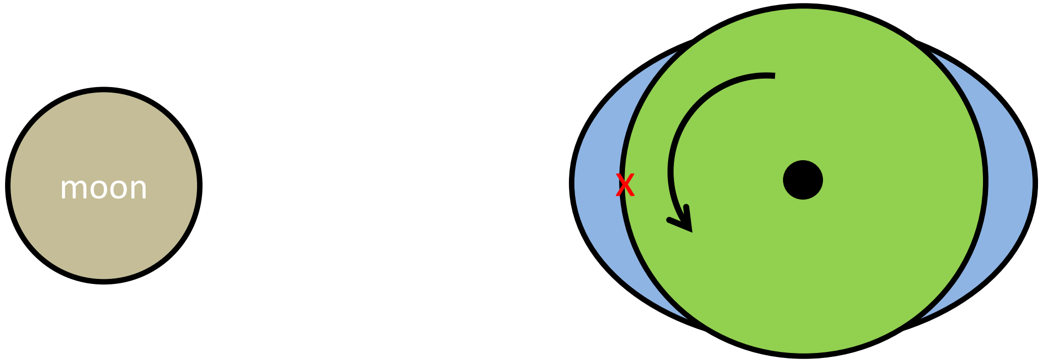
Earth-Moon System



Again, let "X" be at the position shown at 12:00. The following day at 12:00, X will again be at the same position, but the moon will have advanced slightly

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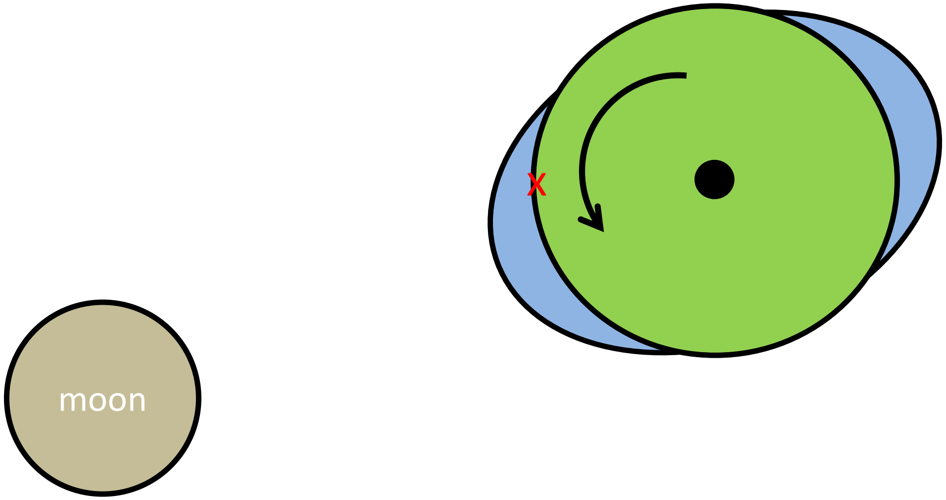
Earth-Moon System



How long will it be before location X experiences the next high tide?

Not to scale. Motion exaggerated.

Tidal Period

- Recall that the Moon orbits the Earth about once every 27.3 days
- Every hour the Moon has advanced approx:

$$w = 360 \times 1 / (24 \times 27.3) = 0.55^{o}$$

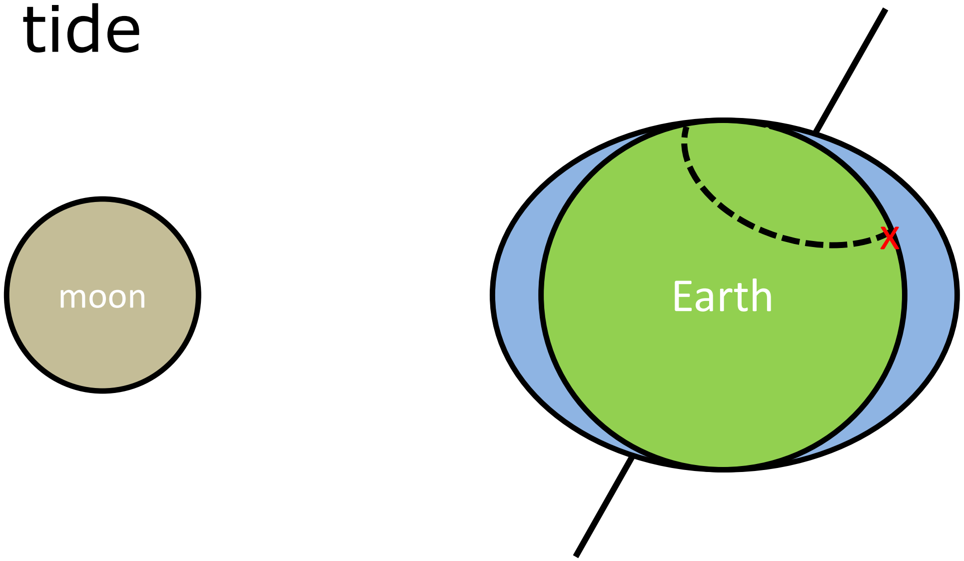
- So that after 24 hours it has advanced: 13.19^{o}
- Since the Earth rotates at 15^{o}/hour, it takes

$24 + 13.19/15 = 24.8$ hours to experience two high and low tides

  - This is why high and low tides do not occur at the same time each day

Tidal Period

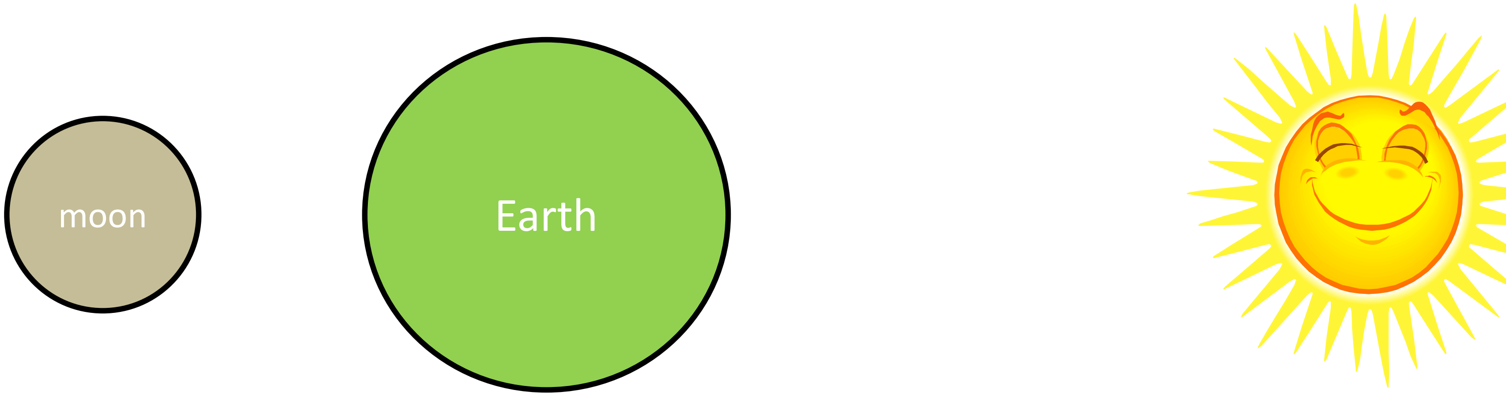
- The mismatch between a solar day and the tidal period is challenge to tidal energy
- Note: because the moon does not orbit the Earth on the plane of the equator, it is possible for some locations at high latitudes to experience one tide



The Sun

- The sun's gravitational effect on the tides is less than the moon's (while more massive, the sun is more distant)
- When the sun and moon are aligned, a higher "spring tide" is experience
  - Spring and neap tides occur approx. twice each month and have nothing to do with the season spring
- When they are perpendicular, a low "neap" tide results
- Ratio of spring to neap tide heights can be 2:1

Spring Tide



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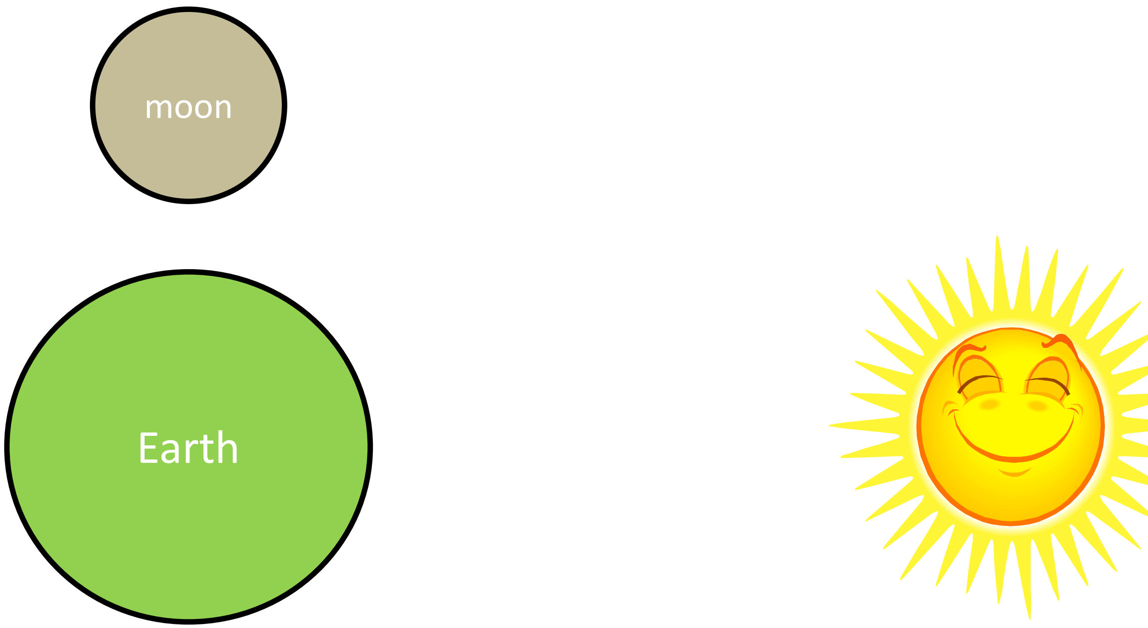
Neap Tide

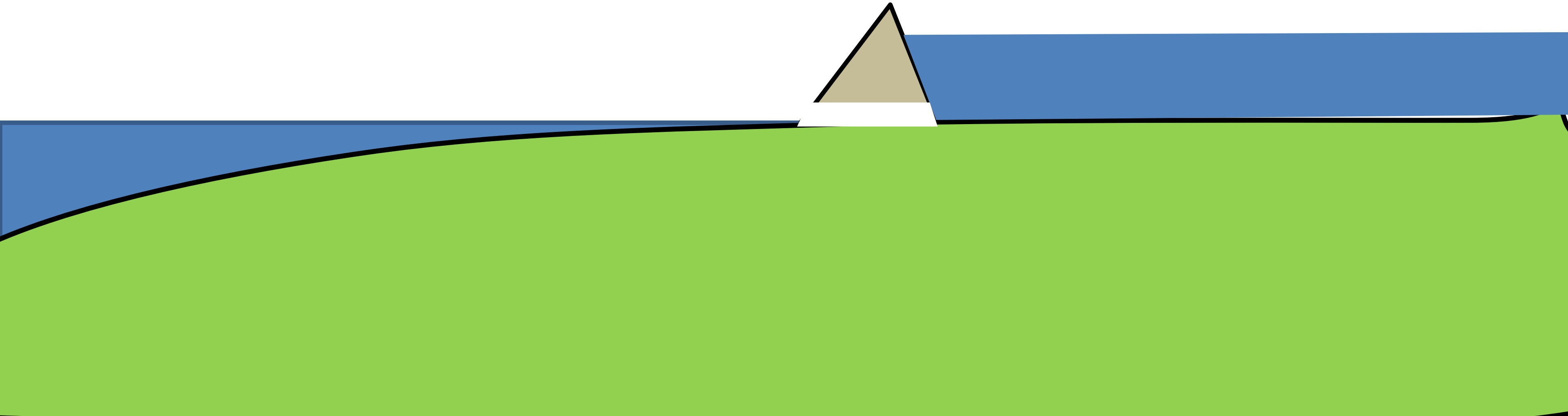


Not to scale

Tidal Range Generation

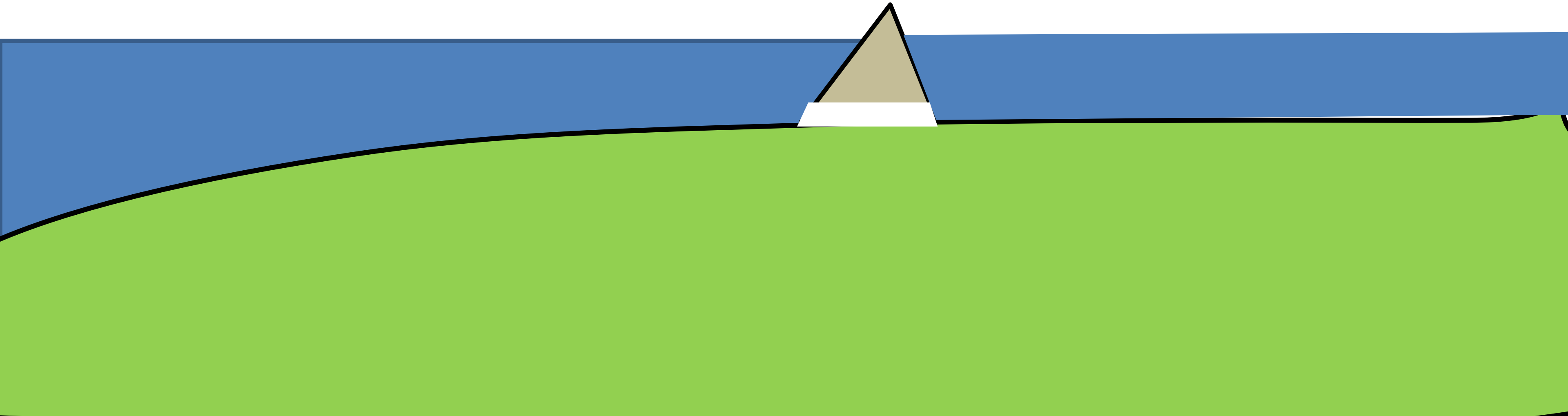
- Tidal action increases the height of water (potential energy) during high tide
- Tidal range: trap water (typically in an estuary) behind a barrage during high tide, and release through a hydro turbine during low tide

Tidal Range Generation



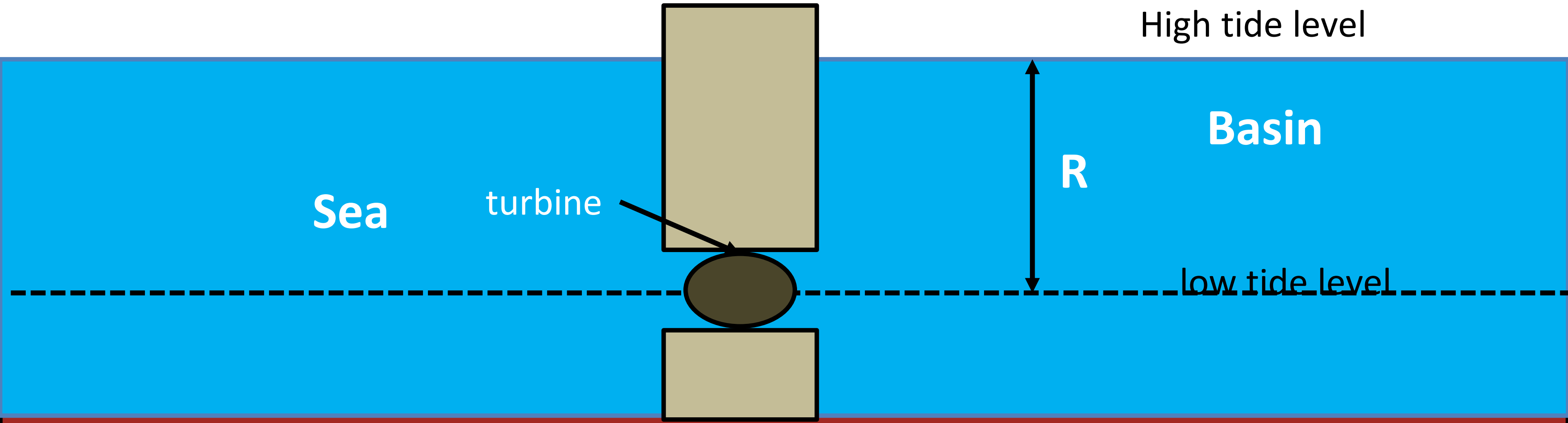
Tidal Range Generation

Water is released to generate electricity



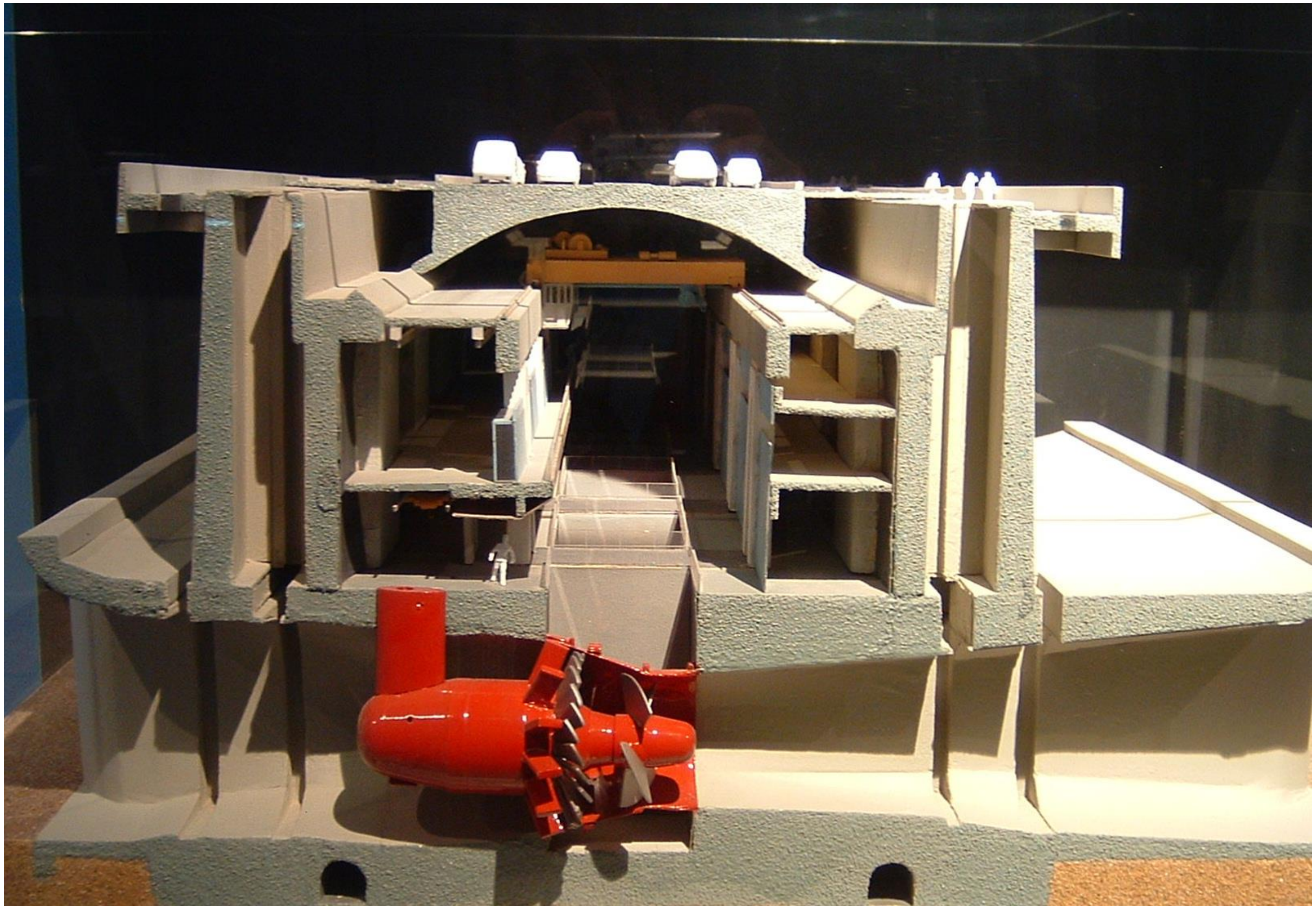
Tidal Range Generation

- Tidal Range: the distance between the high tide and low tide water level
- Tidal range varies across the month (due to neap, spring dynamics, etc.)



La Rance

La Rance



Tidal Range Generation

- The potential energy per tide that is stored in the basin side is:

$$E = \rho ARg(R/2) = 0.5\rho AgR^2$$

  - ρ: density of water, approx. 1025 kg/m^3
  - A: area of the basin
- Note that the height is R/2, not R. R/2 is the average height above low tide (height of the center of mass)

Tidal Range Generation

- It is possible to drain and fill the basin approximately twice per day
- Average power:

$$P_{avg} = \frac{E}{\tau} = \frac{g\rho A R^2}{2\tau}$$

  - τ: tidal period
- Operating the tidal generation using both daily tides doubles the average power generation (τ decreases)

Exercise

Consider a tidal generation scheme where A = $10 km^2$, R = 5m, τ = 12.4 hrs. Compute the average power produced.

Exercise

Consider a tidal generation scheme where A = $10 km^2$, R = 5m, τ = 12.4 hrs. Compute the average power produced.

12.4 hrs = 12.4 x 60 x 60 = 44,640 seconds

10 km = 10 x 1000 x 1000 = 10,000,000 m^2

$$P_{avg} = \frac{E}{\tau} = \frac{g\rho AR^2}{2\tau} = 18\ MW$$

Tidal Range Generation

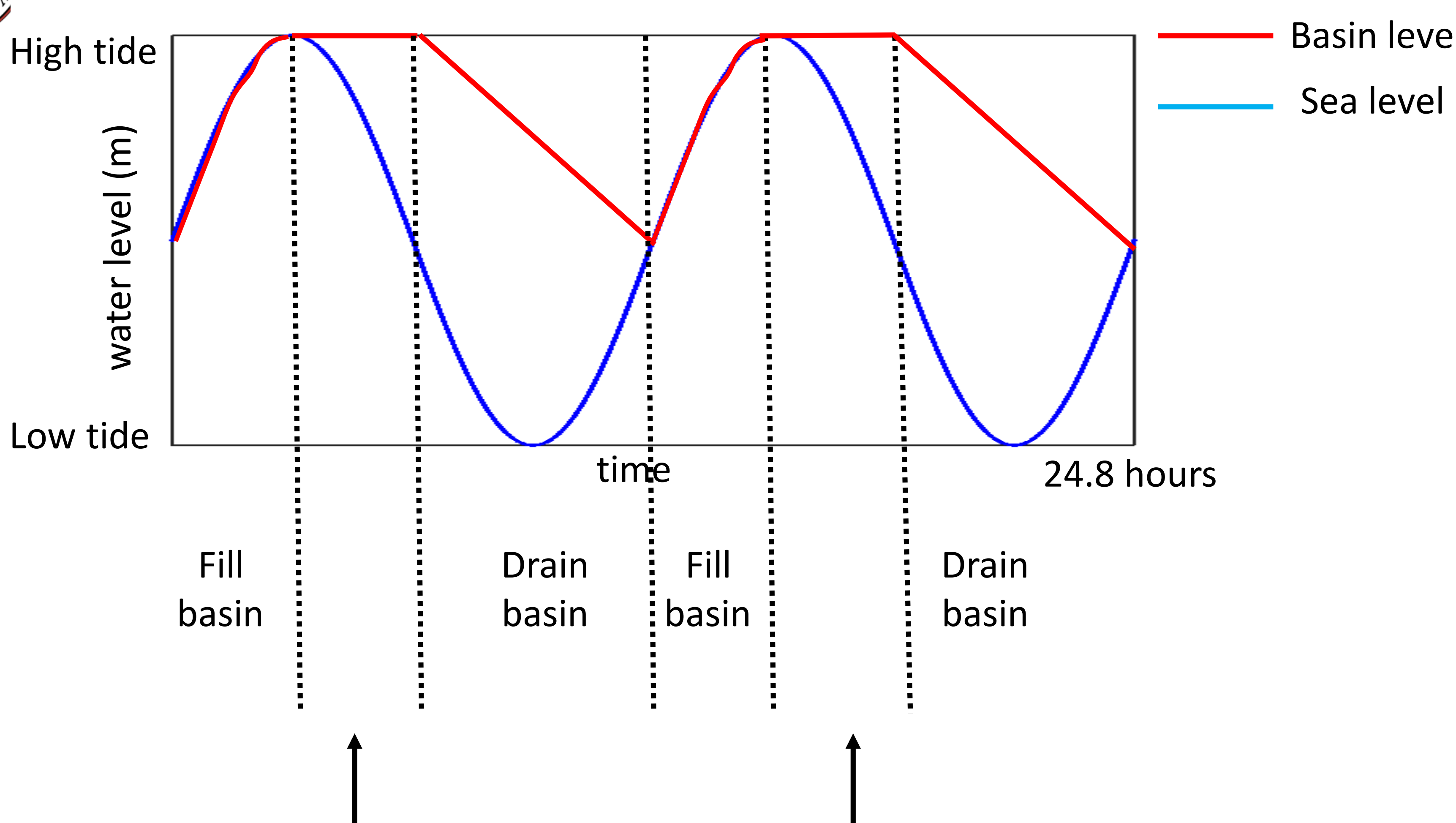
- Average available production will increase with the square of the tidal range
- Average tidal range is about 0.5m, which is very low for tidal range generation
- Locate barrage where tides are amplified by the local conditions (up to 10m)
- Turbine will need to operate at low head, with high volume (similar to a Kaplan turbine)
  - Efficiencies are typically lower at low head

Operation

Three types of operating modes:

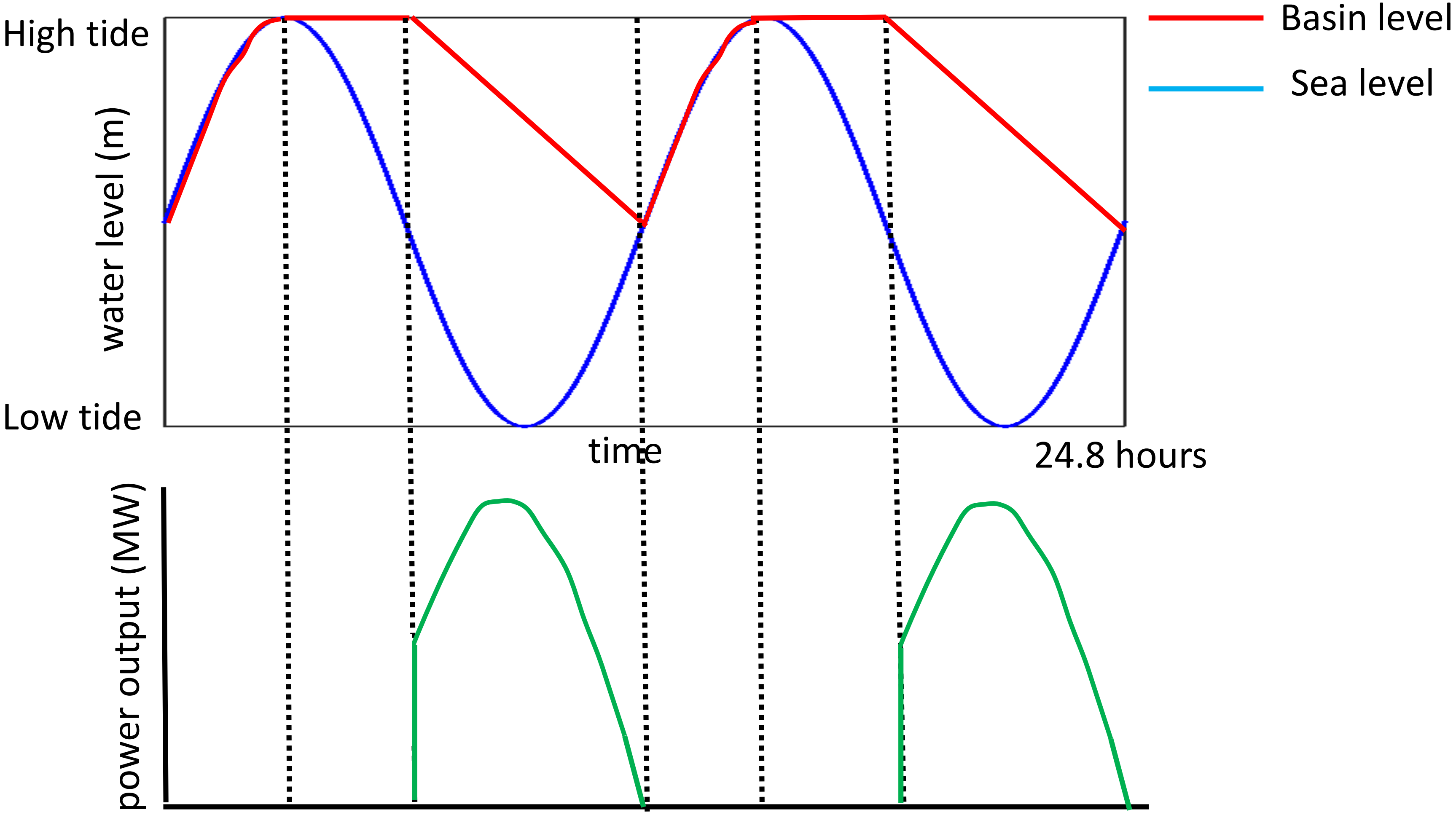
- **Ebb**: high tide fills the basin, water is drained through the turbine during low tide (most common)
- **Flood**: water runs through the turbine during high tide, filling the basin. Water is released during low tide without power generation.
- **Two-way**: water runs through the turbine on entrance and exit (but the basin is filled and emptied more slowly)

Ebb Operation

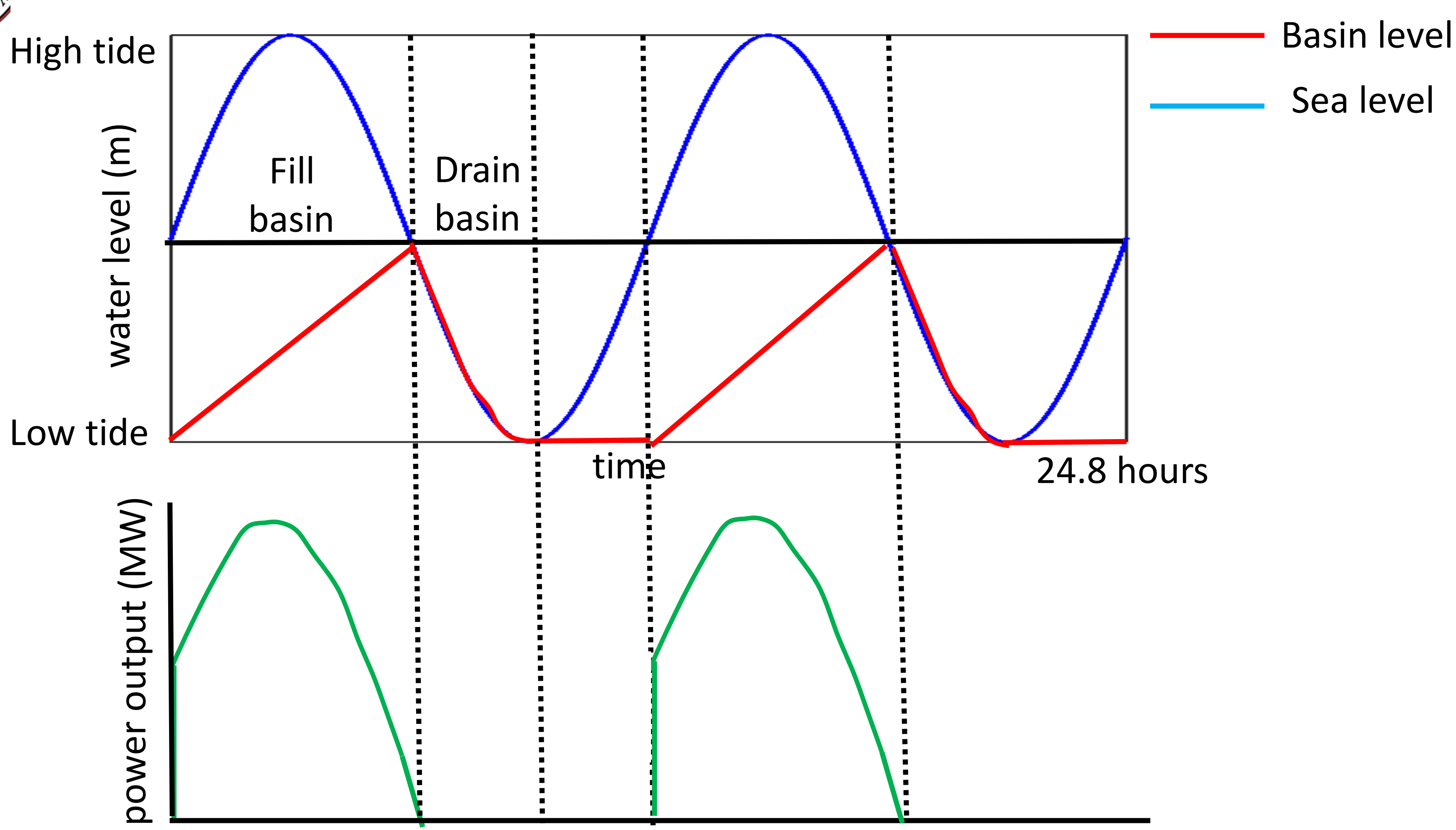


Don't drain here because the difference between basin Level and sea level is small (low potential energy)

Ebb Operation

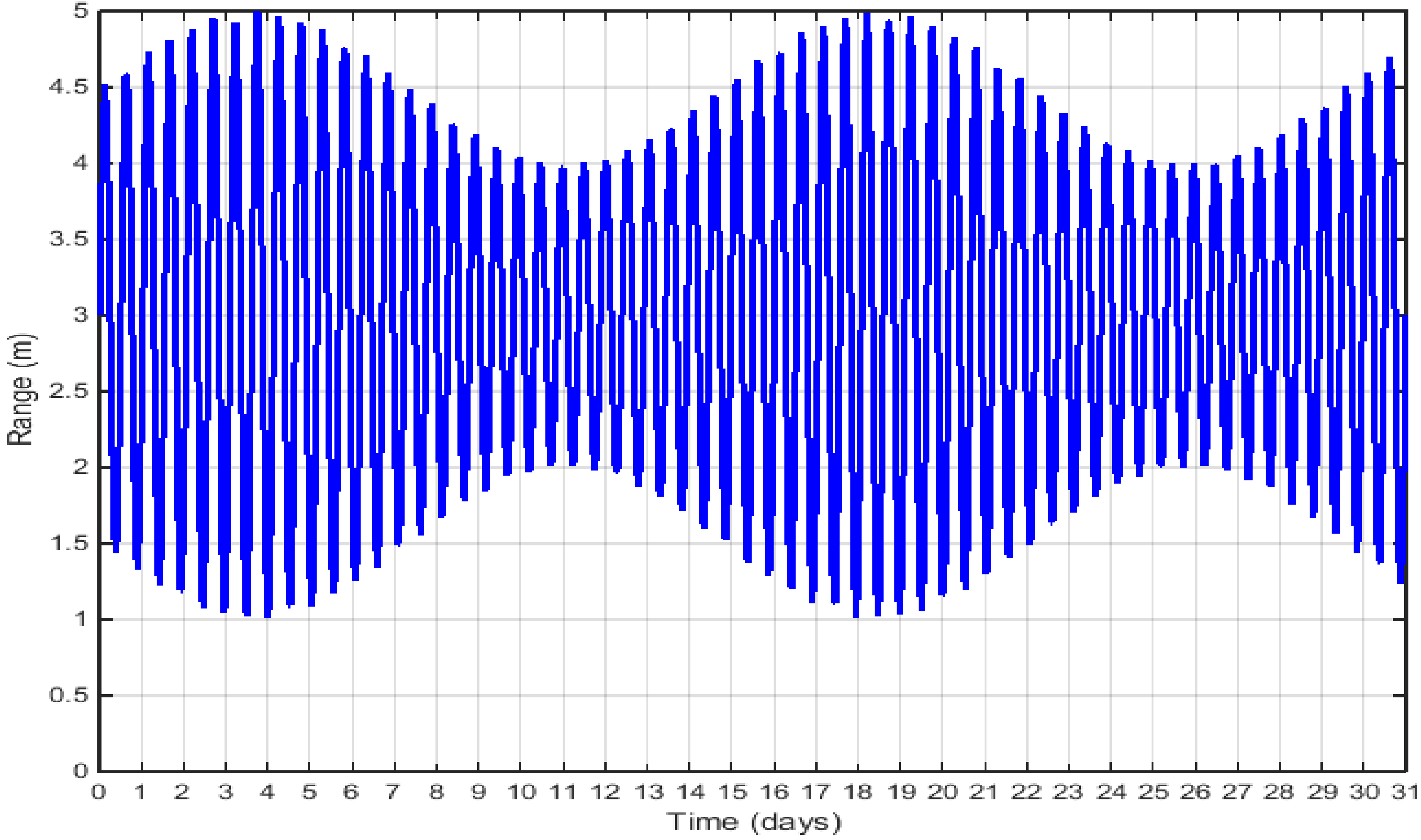


Flood Operation



Operation

- The previous graphs are approximate
- In practice, generation is not possible if the difference in basin and sea level is not large enough
- Turbine efficiency is not constant (varies with head height)
- Density of water may change as fresh water mixes with the more dense sea water



Note: average power over the course of day is different than over the course of a month

Technical Considerations

- Power production is variable (but not uncertain)
  - Cannot be readily dispatched
- 24.8 period of power generation does not synchronize with demand for generation
- Time period for generation is relatively short and head is relatively low—several turbines needed
  - Capacity factor is lower than many sources
- Requirement for very specific tidal enhancement geography may result in tidal generation being far from loads

Economic Considerations

- Large capital costs and timelines associated with barrage construction
- Production cannot start until entire plant is complete—no revenue
  - how does this compare to wind or solar?
- Each installation will be site specific, with potentially widely-varying costs
- If integrated with construction for flood control, cost associated with tidal generation can be reduced

Environmental Considerations

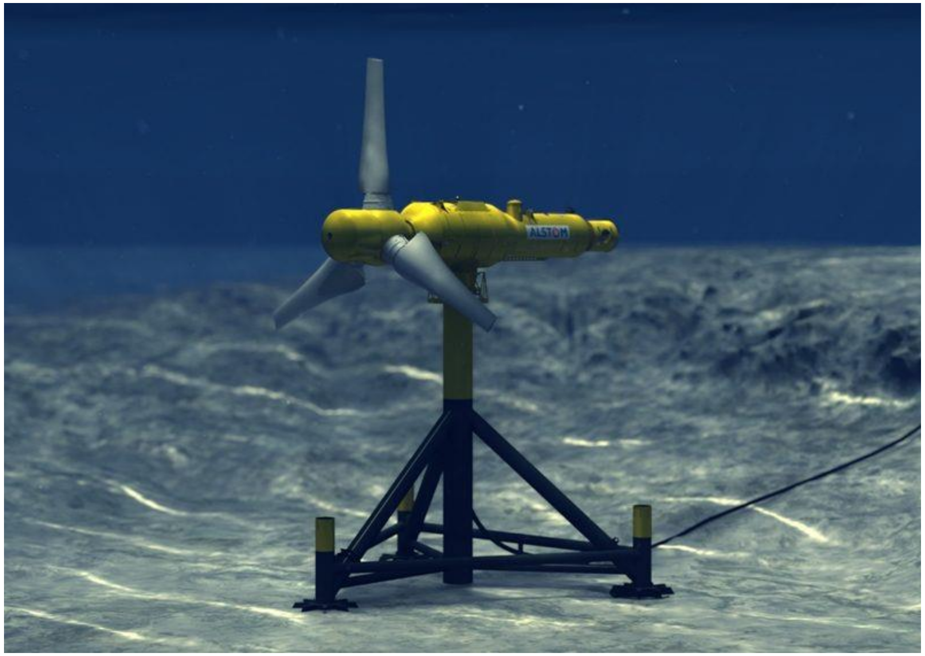
- Reduction of tideland—potentially impacting food supply of birds
- Improved control of basin water level
  - Sailing and other recreation may increase
- Improved flood control of basin side of the barrage
- Barrage can act as a viaduct, allowing vehicle traffic

Tidal Stream

- Harness kinetic energy of undersea moving water (motion caused by tides)
- Velocities of approximately 5 m/s possible
- Energy conversion system similar to wind turbine
- Power in moving water:

  $P = 0.5\rho A v^3$
- Water velocity is less than wind, but the density is ~1000 times greater
  - Much smaller swept area is needed

Example Projects



Source: Alstom

Source: Siemens


180 degree pitch control
to generate power from flood and ebb tide

Tidal Stream--Considerations

- Only a few tidal stream generations under operation
- Can be integrated into bridges and other existing structures
- Environmental considerations:
  - Acoustics could interfere with echo-location
  - Interaction of sea life with turbines