Sustainable Energy

Water Energy

revised from Dr. HS Rajamani and Dr. D.Shepherd

Water Energy - Outline

- Hydroelectricity
  - - History
  - - Principles
  - - Safety, Economic & Environmental considerations
- Pumped Storage
- Tidal Power
  - - Tides & Tidal Power
  - - Barrages
- Wave Power

History of water power

- Potential of water power has been known for more than 2000 years – Roman times
- Early water-mill noted in England in 762 AD
- 1086 Domesday Book recorded 5624 water-mills in England, mainly for
  - Grinding corn
  - Fulling cloth
  - Sawing wood
  - Pumping water
  - Crushing vegetable seeds to extract oil

History of water power

- The Industrial Revolution (late 18th century onwards) saw great use of water-power for cotton & woollen mills and heavy industry.
- Advent of steam power allowed industry to move from where the water-power was located (valleys) to major towns, so water power use declined.
- By 1870 to 1880 water-wheels were used to drive Faraday dynamos – many small generators were driven from streams to provide electric light.

- This house “Cragside” in Scotland was the first house in the world to be lit by hydro-electricity in 1878. Built and subsequently extended by wealthy industrialist William Armstrong from 1863 onwards.

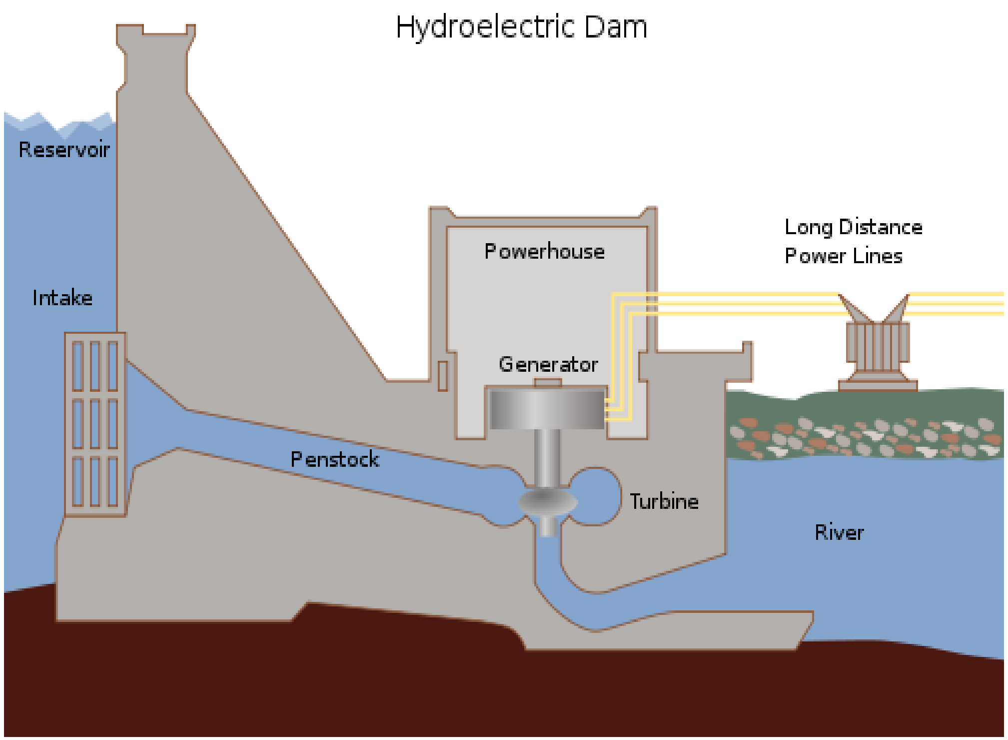
Waterwheel at Buckfast Abbey, Devon provides light and power for a large workshop (few kW).

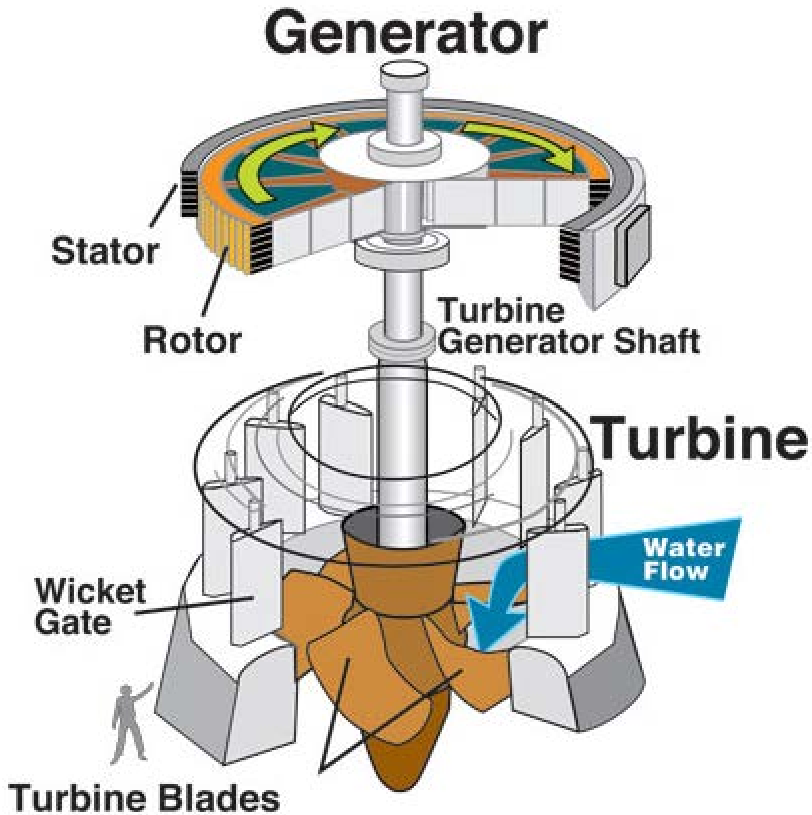
History of water power

- The first commercial “large-scale” plant was 1882 in Wisconsin USA – 12kW capacity for 250 light-bulbs!
- Rapid progress on design of dams and generation equipment led to many hydro-electric projects by the end of 19th century and in the early part of the 20th.
- **By year 2000, hydroelectricity accounted for 755 GW, some 17% of total world electricity generation.**
- New projects especially in Asia and Latin America look set to nearly double this within a few years.

Large hydroelectric plants

- Typical construction





Basic principles

- You need:
  - A “head” of flowing water, *either a)* naturally flowing down a hillside *or b)* provided by a dam
  - A ‘penstock’ to take the water down to the power house
  - Some kind of throttle or regulation device
  - A water-driven turbine to generate electricity
  - An outflow channel to return water safely to its original course or an alternative destination
- Safety considerations usually also require some kind of by-pass to allow excess water volumes to escape.

Large hydroelectric plants

Penstocks

Ohakuri

Dam, N.Z.

Large hydroelectric plants

- Usually 5 to 10 turbine/generator sets, often underground.

Large hydroelectric plants

<u>Hoover Dam</u>

Length = 379 m

Head = 180 m

Capacity ~ 2 GW

Large hydroelectric plants

<u>Niagara River</u>

(Sir Adam Beck

Complex)

5 power stations

Total Capacity

~4.5 GW

Large hydroelectric plants

<u>Three Gorges Dam, China</u>

Length = 2335 m
Head = 113 m
Capacity = 22 GW

Types of hydro plant

- Large plants go from a few hundred megawatts to 10 GW or more. Examples:
  - Three Gorges, China 22.5 GW
  - Itaipu, Brazil 14 GW
  - Guri, Venezuela 10.2 GW
- Small plants – up to 10MW – to serve remote areas, usually based on natural lakes and rivers
- Micro plants – up to 100kW for isolated homes, farms or small communities
- Pico plants – under 5kW, individual homes for lighting and TV and utilities

Large hydroelectric plants

Other uses of hydroelectricity assets can include

- Recreational use of reservoirs and lakes
- Control and storage of water for flood management and irrigation
- Industrial & domestic water supply

It is vital to integrate these different functions to avoid serious environmental and social damage in the long term

- Other proposed schemes have attracted opposition from environmental pressure groups

Small hydroelectric plants

- Very popular China, Japan, USA and India.
- China already has 65 GW supplying thousands of small towns and villages
- Small standardised sets of equipment, minimal civil engineering makes small and micro plants very attractive – quick and cheap to install
- Complements solar power which is less effective in winter, whereas hydro is more effective during winter

Hydroelectric Power - Principles

How much power can you get?

- Theoretical maximum power can be calculated by assuming that all the potential energy is available
- Power (kW) approximately = 10 x Q x H
  - Q = cubic metres water per second
  - H = height ('head') through which water falls
- More precisely = Q x H x density x *g* (*g* = 9.81 ms^{-2})
- Can have large Q, small H or large H, small Q for same power output

Hydroelectric Power - Principles

Water falls under gravity	Potential Energy -> Kinetic Energy		(1)
Volumetric Flow Rate	Q = volume/time	m^3/s	(2)
Gravitational P.E.	$W_p = m.g.h$	joules	(3)
Water density	ρ		
Mass	$m = Q.\rho$		(4)
=>	$W_p = Q.\rho.g.h$	J/s	(5)

K.E. acquired by water mass m, initial velocity of zero, final velocity V

$$K.E. = \tfrac{1}{2}\, m.V^2 \qquad (6)$$

From (1), (3), (6)

Water velocity on impact $\quad V = \sqrt{(2.g.h)} \qquad (7)$

Hydroelectric Power - Principles

Efficiency

Example

Typical Penstock Efficiency $\eta_p = 90\%$

Typical Turbine Efficiency $\eta_t = 90\%$

Typical Generator Efficiency $\eta_g = 95\%$

Total Efficiency $\eta_{total} = \eta_p \cdot \eta_t \cdot \eta_g$ (8)

$= 0.90 \cdot 0.90 \cdot 0.95$

$\mathbf{= 0.77}$

Typical {Water-Head – Penstock – Turbine – Generator} *efficiency is 70% - 80%, --> much higher than the efficiencies of wind turbines or any heat-work system.*

Hydroelectric Power - Principles

Worked Example 1

For a head of water of 400m, with volumetric flow rate 50 m^3/s, Calculate P(out) if overall efficiency is 70%, and water velocity at impact (neglecting losses). (Density of water = 1000 kg/m^3, g = 9.81 m/s^2)

Volumetric Flow Rate $Q = 50\ m^3/s \Rightarrow 50{,}000\ kg/s$

Potential Power $= Q.\rho.g.h$

$= 50 \,.\, 1000 \,.\, 9.81 \,.\, 400$

$= 196.2 \times 10^6$ J/s

$= 196.2$ MW (no losses)

Output Power P(out) = potential power * efficiency

$= 196.2 * 0.70$

$\underline{= 137.3\ \text{MW}}$

Hydroelectric Power - Principles

Worked Example 1 (contd)

Final Velocity of Water (neglecting losses)

$$V = \sqrt{(2.g.h)}$$

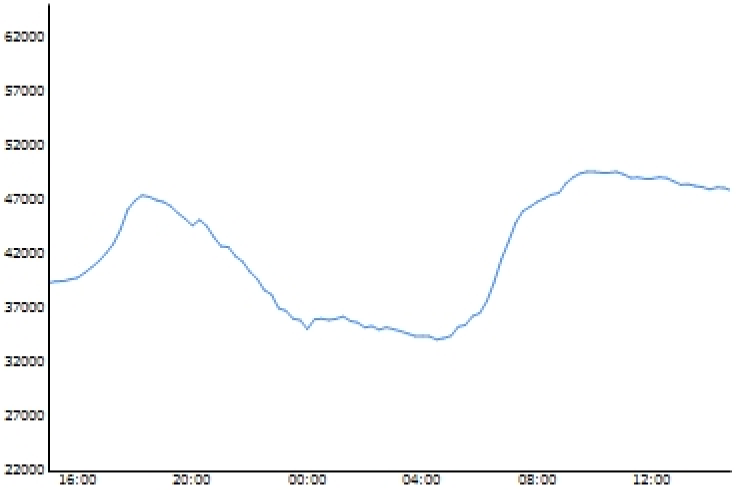
$$= \sqrt{(2 \, . \, 9.81 \, . \, 400)}$$

$$= \underline{88.6 \text{ m/s}}$$

Pumped Storage

Conventional Generation System

- Peak load on electricity generation system occurs in daylight hours (industrial & domestic).
- Daytime load > Night-time load
- Installed generation must cover max. demand.
- At night, expensive generators are underused (poor utilisation factor) and cheap 'off-peak' electricity is available.



Pumped Storage schemes

- At night, generators drive pump motors to pump water into high reservoirs.
- Stored head of water tapped during day to top-up and smooth out supply at peak hours
- "Stores electricity" thus reducing the need for extra generators.

Pumped Storage

Economics & Logistics

- Pumping water uphill with electricity to release it downhill to generate electricity not only sounds crazy, the 75% efficiency of the pump-release cycle means energy is lost.

- Financial savings (made from not needing extra generators) must *exceed* the total costs (of installing and operating the pumping system).
- Provides vital quick-response backup in case of sudden supply failure.
- Offers solution to problem of overgeneration by wind turbines.

UK Pumped Storage

Dinorwig, Wales, UK. Head = 568m, 6 units x 300 MW -> rated at ~1.8 GW.

Delivers output for 6 hours. On-stream time = 15 seconds.

World Pumped Storage

World's largest installations are rated at 2-3 GW – in Japan & USA.

Tidal Power

<u>TIDES</u>

Fundy Bay, Canada

High Tide

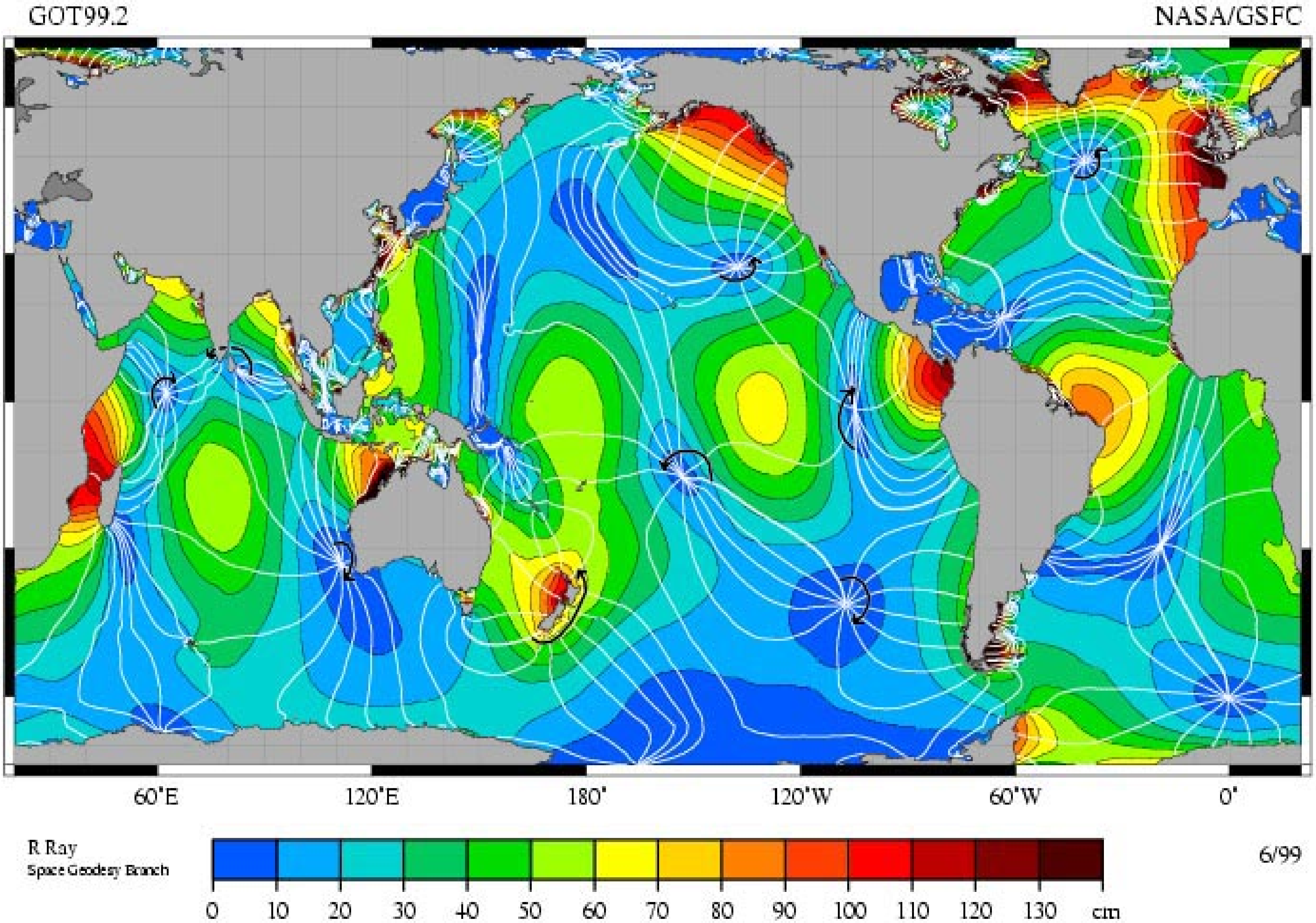
Tidal Power

Fundy Bay, Canada

Low Tide

Tidal "Range" ~15m

[Next slide: Tidal Range in world's oceans]

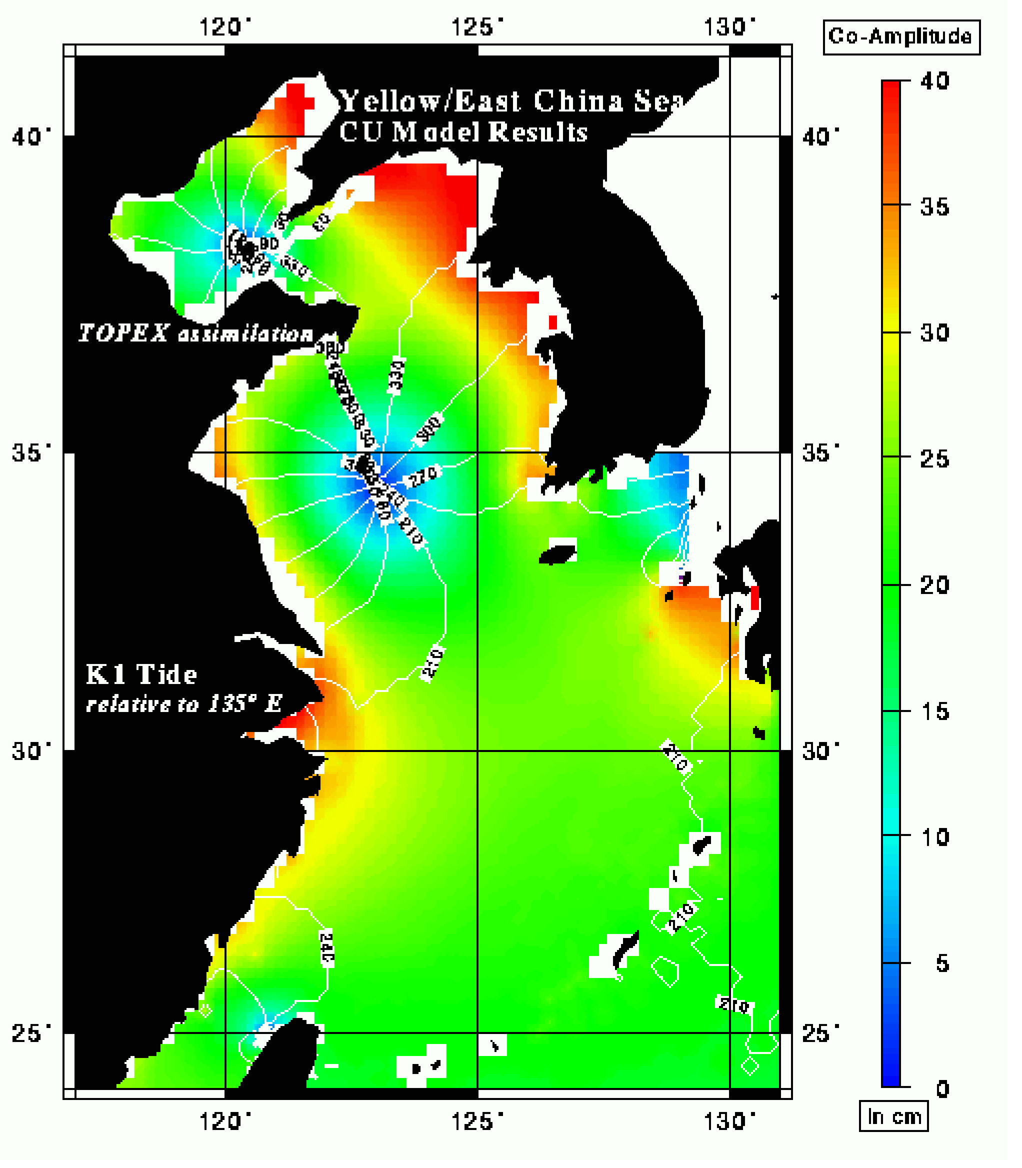


GOT99.2
NASA/GSFC
60°N
30°N
0°
30°S
60°S
60°E
120°E
180°
120°W
60°W
0°
R Ray
Space Geodesy Branch
0
10
20
30
40
50
60
70
80
90
100
110
120
130
cm
6/99

Tidal Power

Tidal Range Map

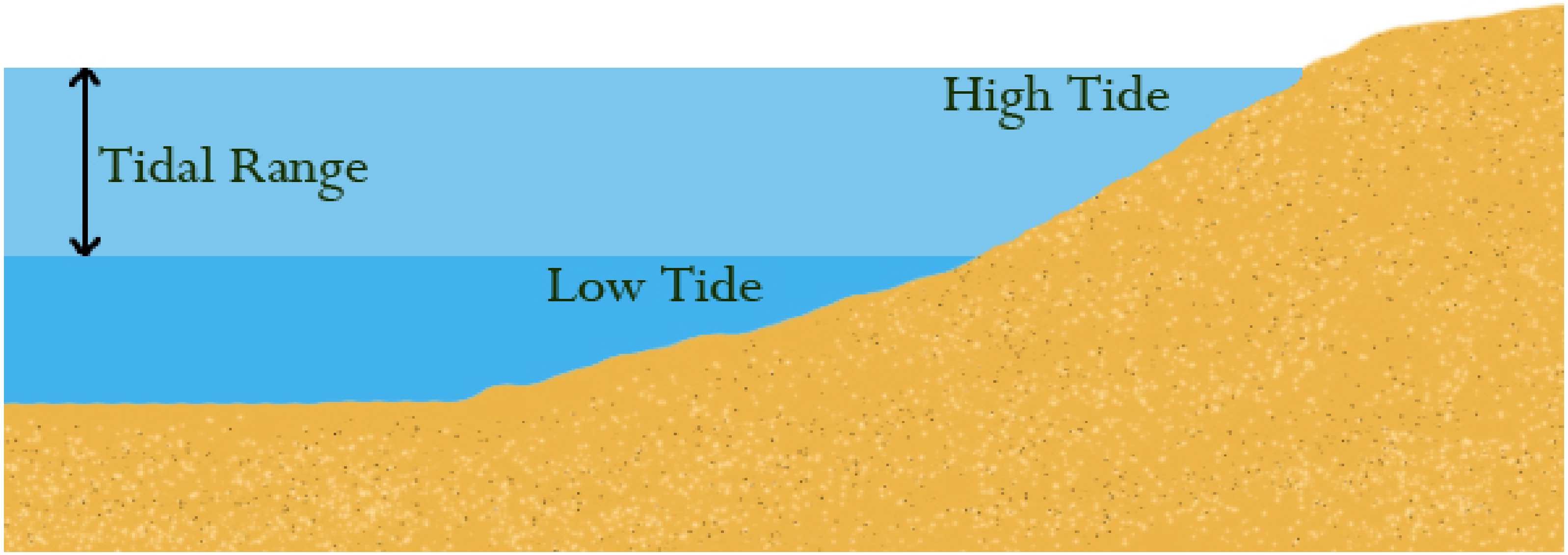
Yellow Sea



Tidal Power

Tidal Range

Tidal Basin (area A)



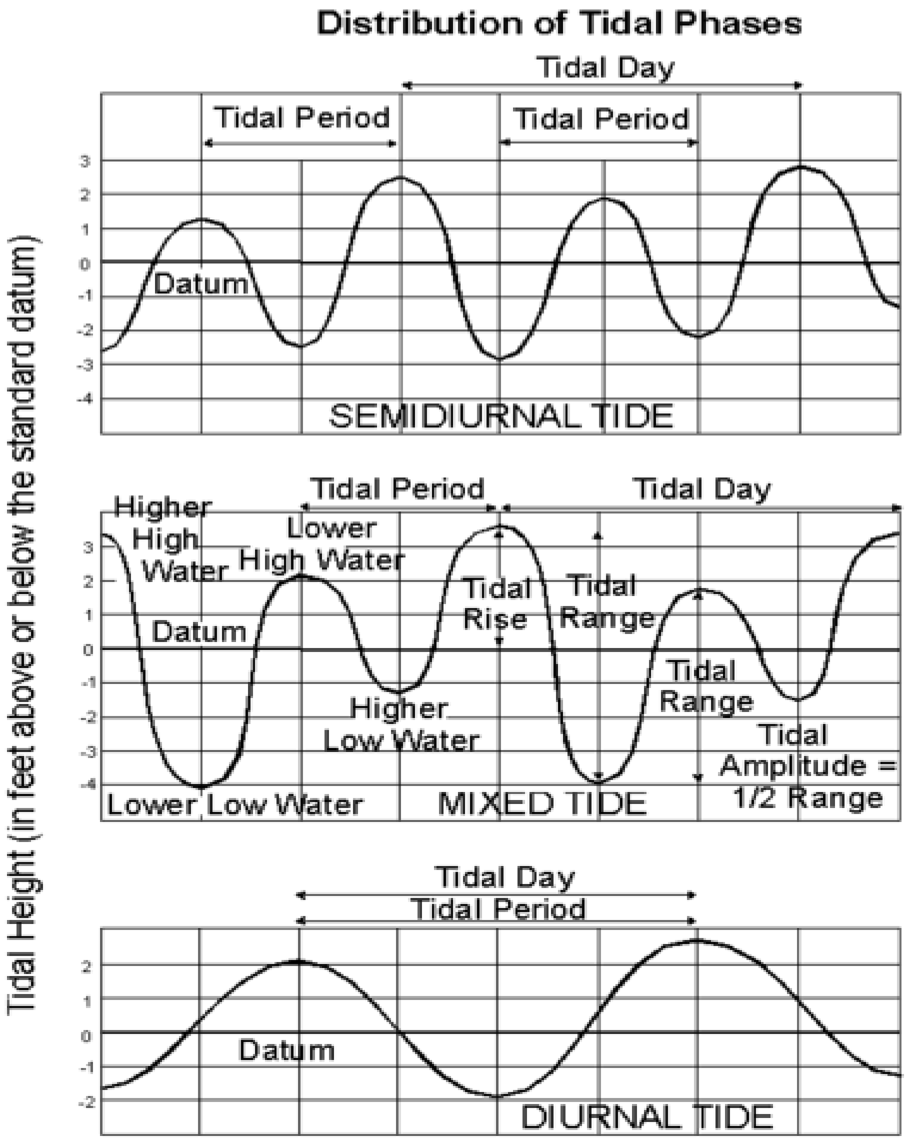
Tidal Phases

Tides depend on:

- Moon
- Sun
- Bathymetry (sea depth & profile)

Tidal Day ~24.8 hr

Very Complex!



Tidal Barrages

- By damming a river estuary it is possible to get a huge flow of water across a small head (typically 5-15 metres)
- Largest barrages: France (1966), S.Korea (2011)
- Although the dam (or barrage) is low it may be very long
- Only generates for about 10 hours/day but is very reliable.
- May have huge environmental impact on the river estuary so has been seen as controversial.

Tidal Barrages

Rance Tidal Power Station, France.

10x24 MW turbines, R = 8m.

L = 700m A = 22 km^2

Sihwa Lake TPS, S.Korea

10x25.4 MW turbines, R = 5.6m

L = 12700 m* A = 43 km^2

Construction cost ~ US$ 280M*

(* made use of existing sea wall/islands)

Tidal Barrages

Severn Barrage, UK (Proposed)

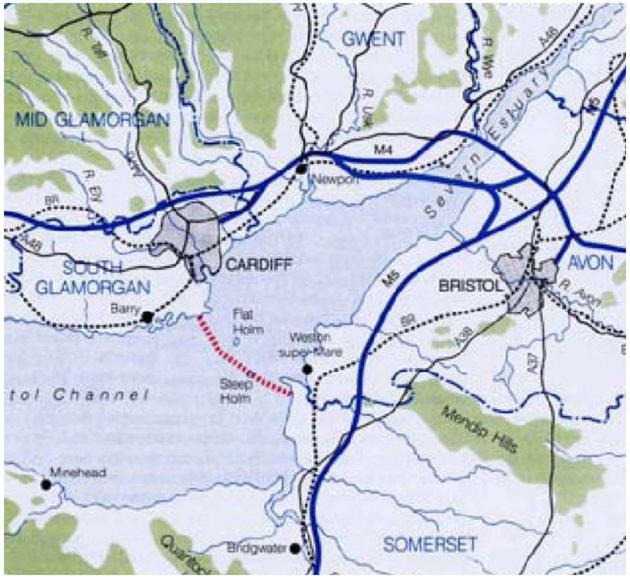
L = 16000 m A = 150 km^2

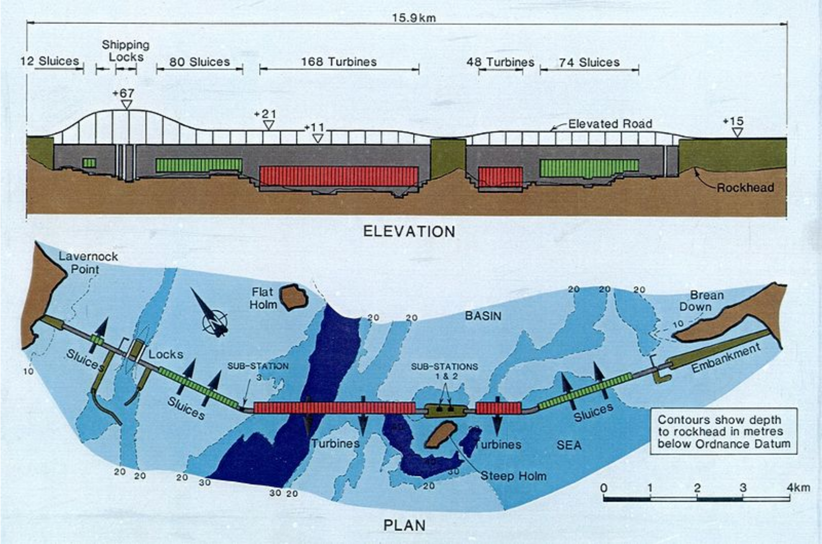
Capacity 8.6 GW

Lifetime ~ 120 y

Est. construction cost £10-35bn

Upkeep cost = {comparable to 1.5 nuclear power stations}.



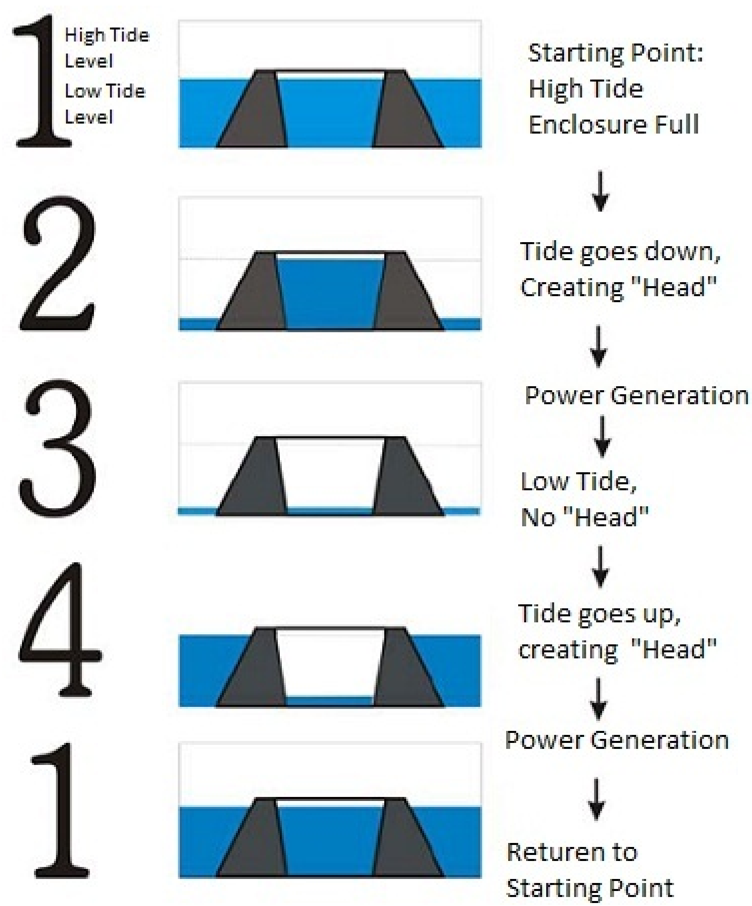


Tidal Lagoons

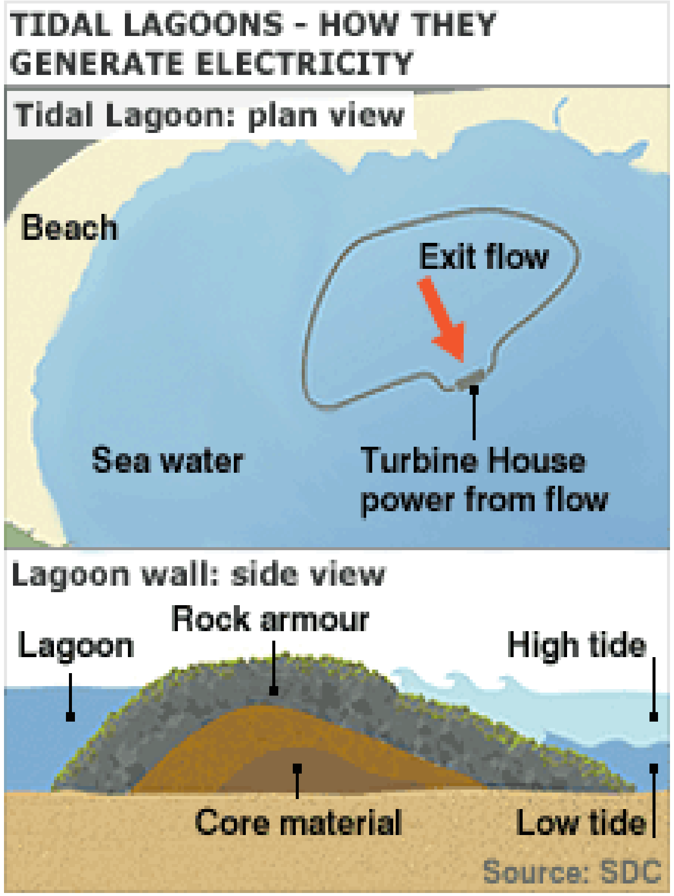
•Artificial Lagoon uses tidal/sluice capture without blocking an estuary.

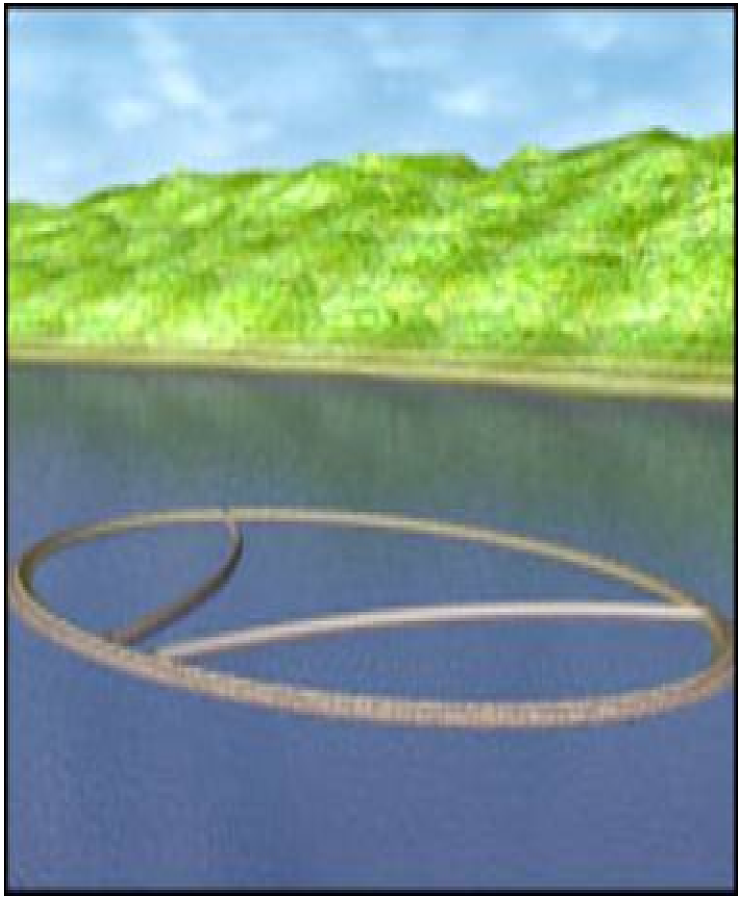
•Far more popular with environmentalists because estuary is less drastically effected.

•Tidal flow around lagoons may be constricted causing stronger, more erosive flow.



Tidal Lagoons





Some interesting technologies

https://www.youtube.com/watch?v=W7PTx0W66dM

https://www.youtube.com/watch?v=ZPi9HeDgN58

https://www.youtube.com/watch?v=gcStpg3i5V8

https://www.youtube.com/watch?v=ZTZlbUb-4kY

https://www.youtube.com/watch?v=YKumDZwLziw

Safety issues

- Various causes of dam failures are
  - Poor hydrological and geological design
  - Poor construction – scope for corruption and use of poor quality materials, unskilled labour
  - Earthquakes
  - Failure due to flash floods
  - Sabotage
  - “Enemy action” in times of war

Safety issues

- In USA alone, between 1918 and 1958 no less than 1600 people died as a result of dam failures; comparable with coal industry in same period. *(Ref: Shepherd & Shepherd p55)*
- In August 1975, catastrophic failure of a series of 62 dams in Henan Province of China caused 58,000* deaths and made 11 million people homeless.
- These are low-probability, severe consequence events.

Environmental issues

- Dams may have severe effects on rivers both upstream and downstream.
- Upstream - due to flooding and diversion of rivers.
- Downstream– sewage, silt, lack of flow at various times, reduced erosion.
- Dam itself may lose water by evaporation – Aswan dam loses 10% of all water flow, denied to downstream farmers.
- May relieve the effects of seasonal flooding.

Environmental issues

- A hydroelectric power station may look benign, the potential for ecological damage is huge because a large area of land may need to be flooded.
  - Loss of land and fragmentation of habitat as reservoir fills up.
  - Severe disruption of fish migration paths – e.g. mature salmon cannot access upstream spawning grounds, young salmon killed by downstream passage through turbines (problem cured by ‘fish ladders’/intake filters).
  - Fluctuation of flow downstream causes problems of erosion and damage to riverbanks.

Environmental issues

- Water temperature & oxygen content may change – disrupts the aquatic fauna and flora.
- Upstream river may carry silt into reservoir – buildup may eventually cause problems.
- Downstream flow rates reduce because of evaporation from large surface area of reservoir (compared to pre-existing river).
- Methane from decaying drowned vegetation can be significant – ideally, clear site <u>before</u> flooding.
- Zero emissions of toxic or greenhouse gases during operation.

Economics

- Although hydroelectricity seems to use “free” resources, the initial investment required is huge.
- Once built it provides reliable and cheap power for the lifetime of the plant (long!) and is overall very competitive with long-term price stability.
- Power can be regulated very easily to track demand and if combined with pumped-energy storage add security to electricity supplies.
- May be affected by long-term climate change.
- Tourism side-benefits (Hoover Dam 7M/year)

Economics

- Has best pay-back factor of all means of electricity generation
- If new road is provided, this may improve local economy.
- May attract commercial/industrial development.
- It is a well-established and mature industry

Current hydroelectric capacity accounts for about one third of the economically feasible hydro energy - this supplies ~ 21% of world demand for electricity.

Hydroelectric Production (2014)

Ten of the largest hydroelectric producers as at 2014.[52][54][55]

Country	Annual hydroelectric production (TWh)	Installed capacity (GW)	Capacity factor	% of total production
China	1064	311	0.37	18.7%
Canada	383	76	0.59	58.3%
Brazil	373	89	0.56	63.2%
United States	282	102	0.42	6.5%
Russia	177	51	0.42	16.7%
India	132	40	0.43	10.2%
Norway	129	31	0.49	96.0%
Japan	87	50	0.37	8.4%
Venezuela	87	15	0.67	68.3%
France	69	25	0.46	12.2%

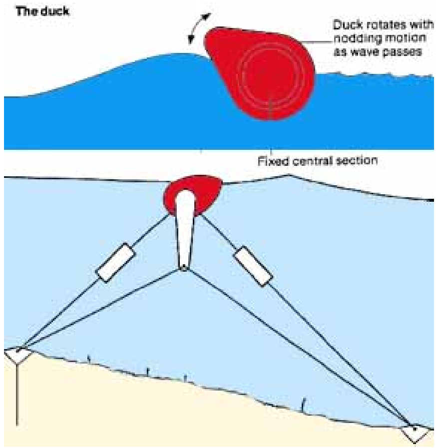
Wave Power

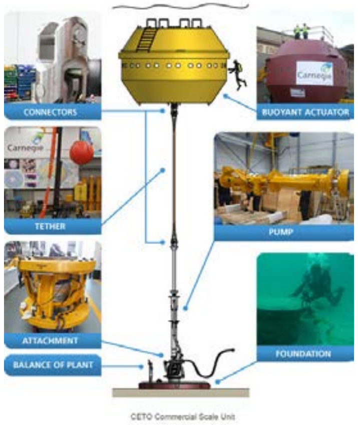
Motion of waves used to move machines.

Mechanical energy converted to electrical

1-20 MW capacity, only viable for remote areas.

Wave Power


The duck
Duck rotates with nodding motion as wave passes
Fixed central section


CONNECTORS
BUOYANT ACTUATOR
TETHER
PUMP
ATTACHMENT
FOUNDATION
BALANCE OF PLANT
CETO Commercial Scale Unit

Hydro Power - Summary

•Advantages

•Fuel supply ‘infinitely’ sustainable.

•Zero CO^2 emissions during operation

•Zero toxic emissions

•Zero waste by-products

•Long plant lifetime

•Fast on-stream response

•Pumped storage can smooth peak demand and act as emergency reserve

•Disadvantages

•Needs hilly terrain or large river flow.

•Ecological / Hydrological disruption both upstream and downstream

•V. high initial investment needed.

•Disruption to shipping.