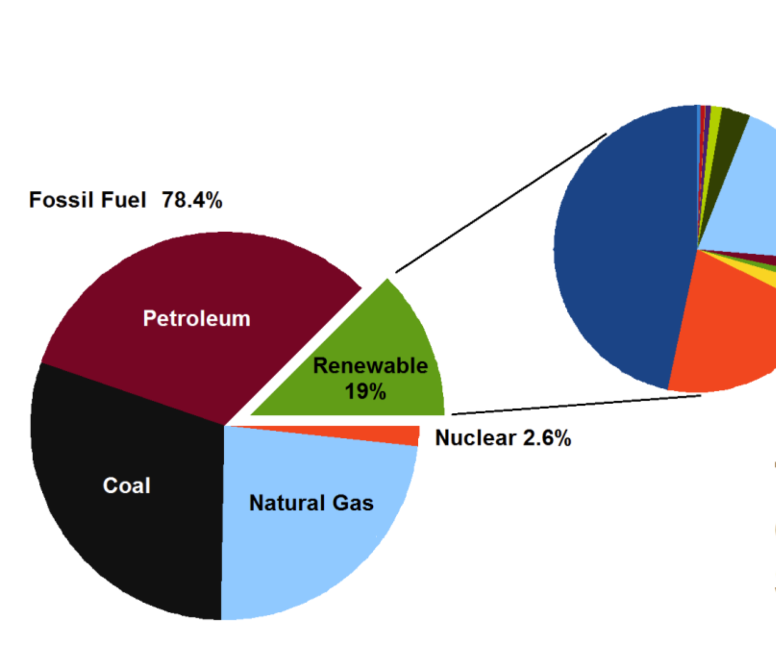
Renewable Energy


Three Gorges Dam



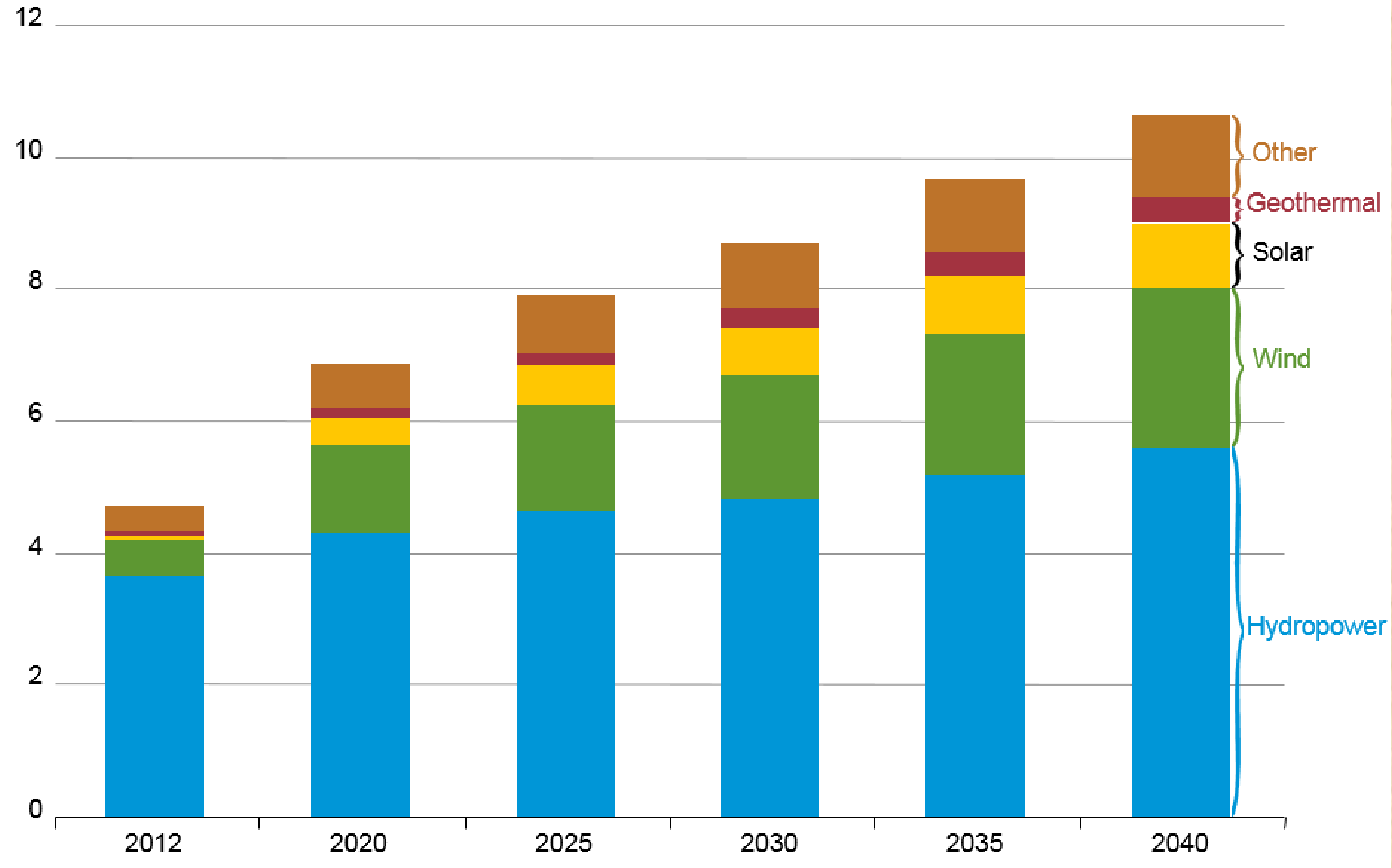
Total World Energy Consumption by Source (2013)

Renewable Energy Technologies
Hydro
Biomass
Geothermal
Wind
Solar heating and thermal electric
Photovoltaic (PV)
Ocean tidal and tidal current
Ocean wave
Ocean thermal electric

Renewable Energy Characteristics
Ubiquity of energy sources
Low intensity of energy fluxes captured compared with conventional systems
Random, intermittent nature of energy fluxes
High capital cost per unit of power output compared with conventional sources

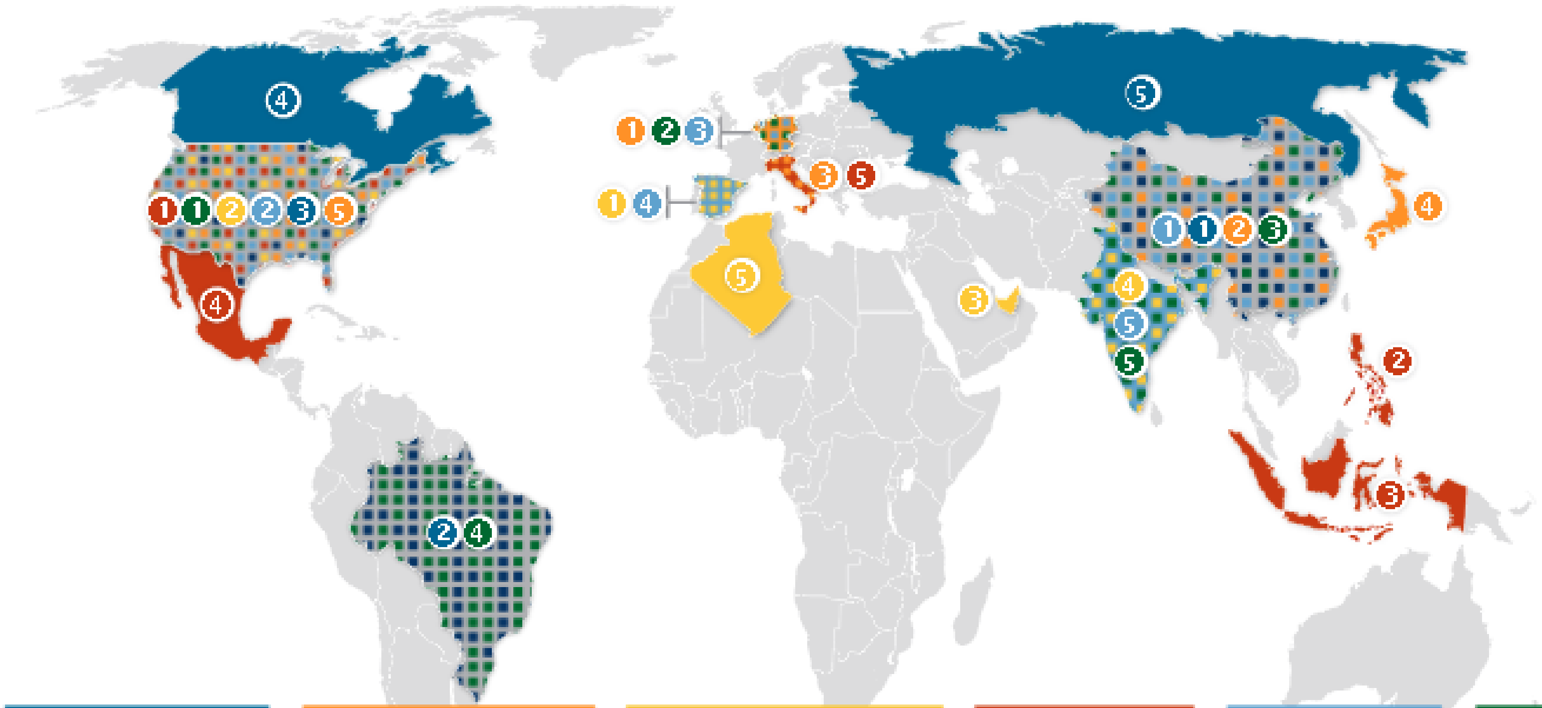
Figures of Merit for Optimizing Renewable Energy Systems
Effectiveness – fraction of renewable resource that is collectable by the system
Capacity factor – long-term average power output/rated power output

Figure 5-4. World net electricity generation from renewable power by fuel, 2012–40
trillion kilowatthours



Top Countries with Installed Renewable Electricity by Technology (2013)

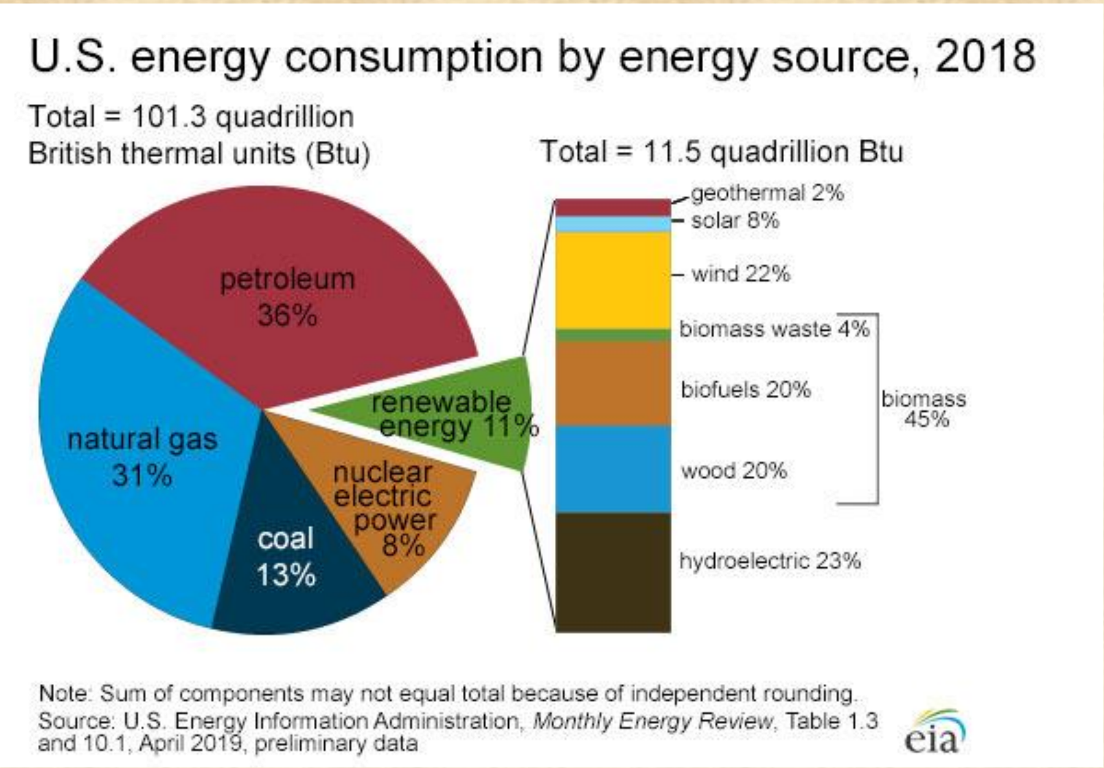
III

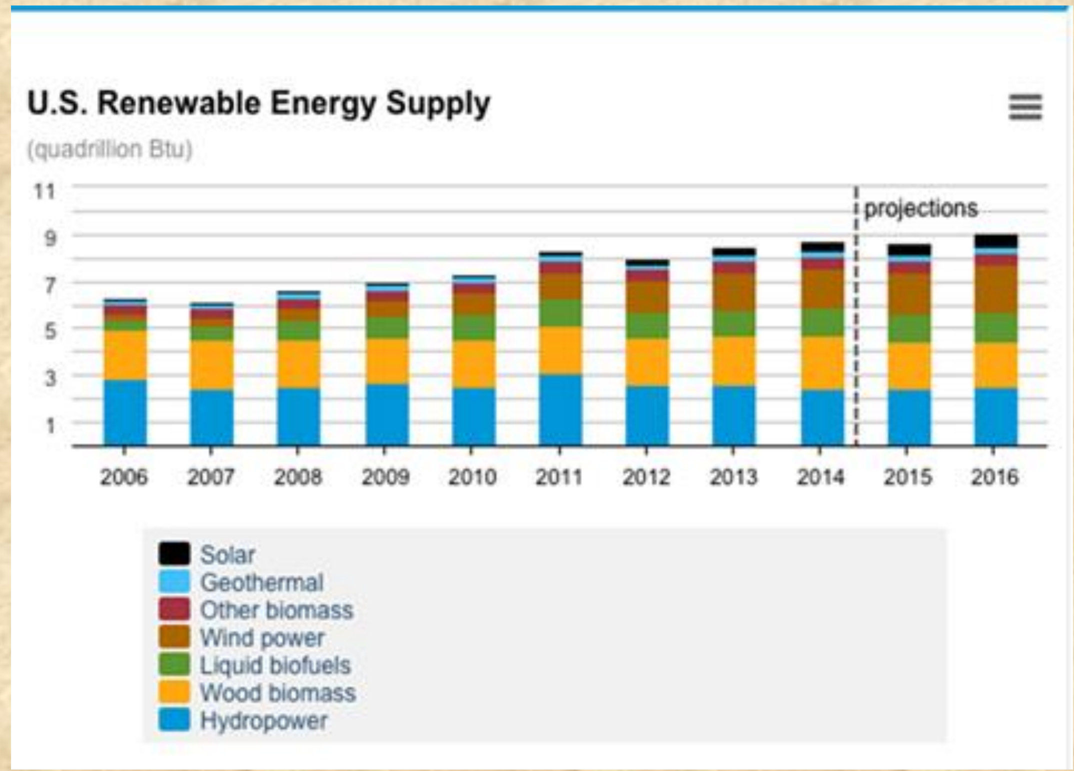


	Hydropower	Solar PV*	CSP	Geothermal	Wind	Biomass
1	China	Germany	Spain	United States	China	United States
2	Brazil	China	United States	Philippines	United States	Germany
3	United States	Italy	United Arab Emirates	Indonesia	Germany	China
4	Canada	Japan	India	Mexico	Spain	Brazil
5	Russia	United States	Algeria	Italy	India	India

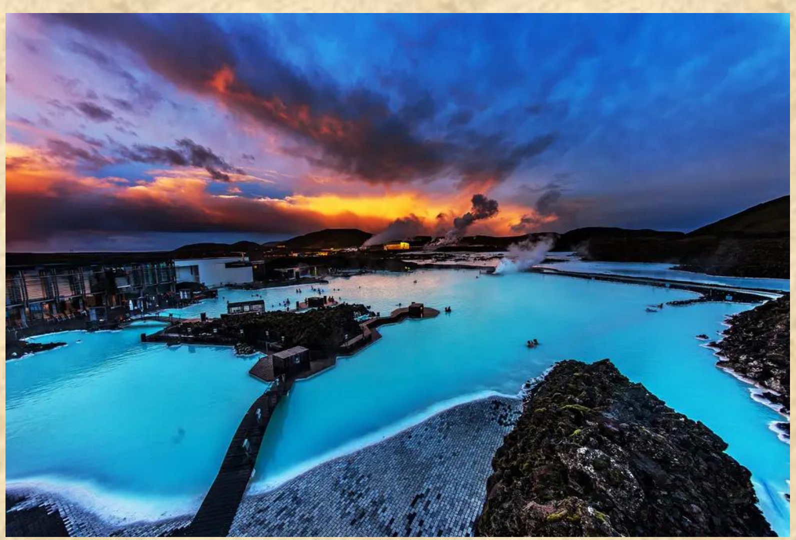
Sources: REN21

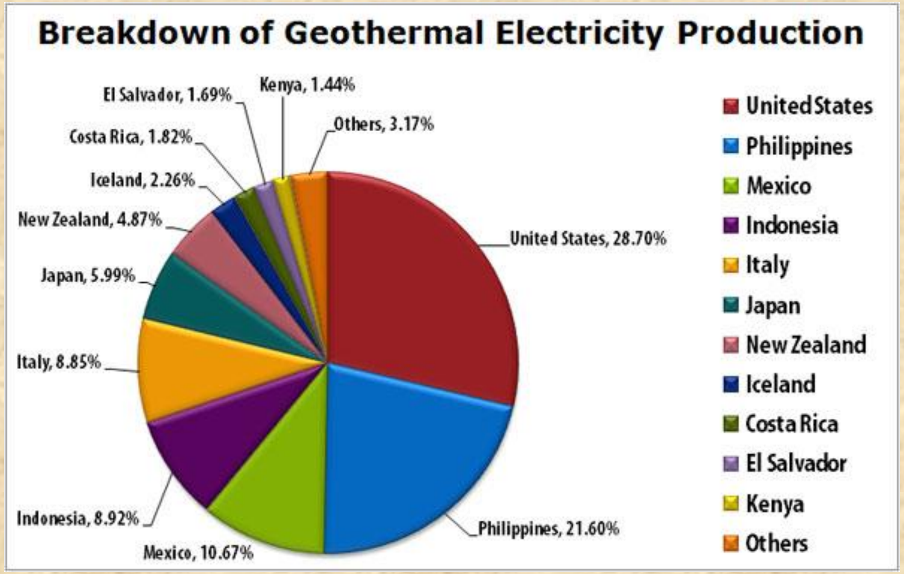
*Grid-connected only

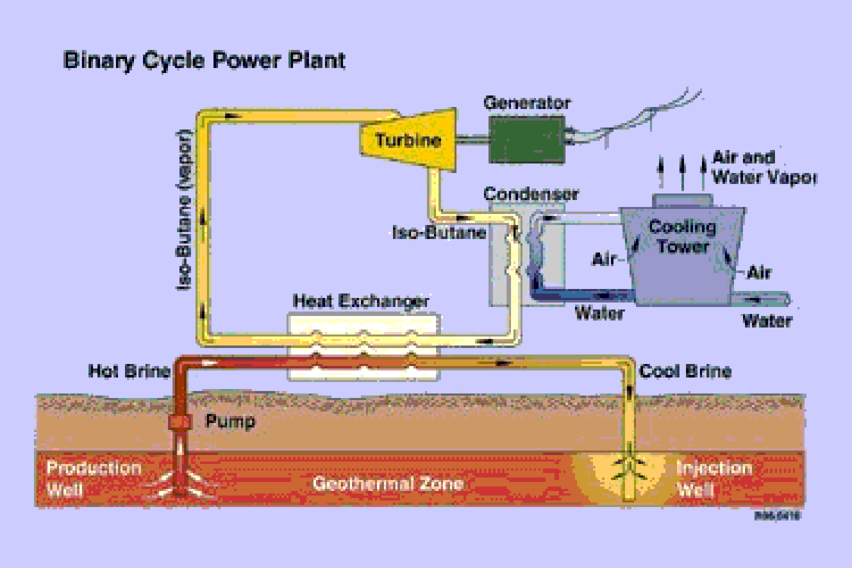

U.S. energy consumption by energy source, 2018
Total = 101.3 quadrillion
British thermal units (Btu)
Total = 11.5 quadrillion Btu
petroleum
36%
natural gas
31%
renewable
energy 11%
nuclear
electric
power
8%
coal
13%
geothermal 2%
solar 8%
wind 22%
biomass waste 4%
biofuels 20%
wood 20%
biomass
45%
hydroelectric 23%
Note: Sum of components may not equal total because of independent rounding.
Source: U.S. Energy Information Administration, Monthly Energy Review, Table 1.3
and 10.1, April 2019, preliminary data
eia

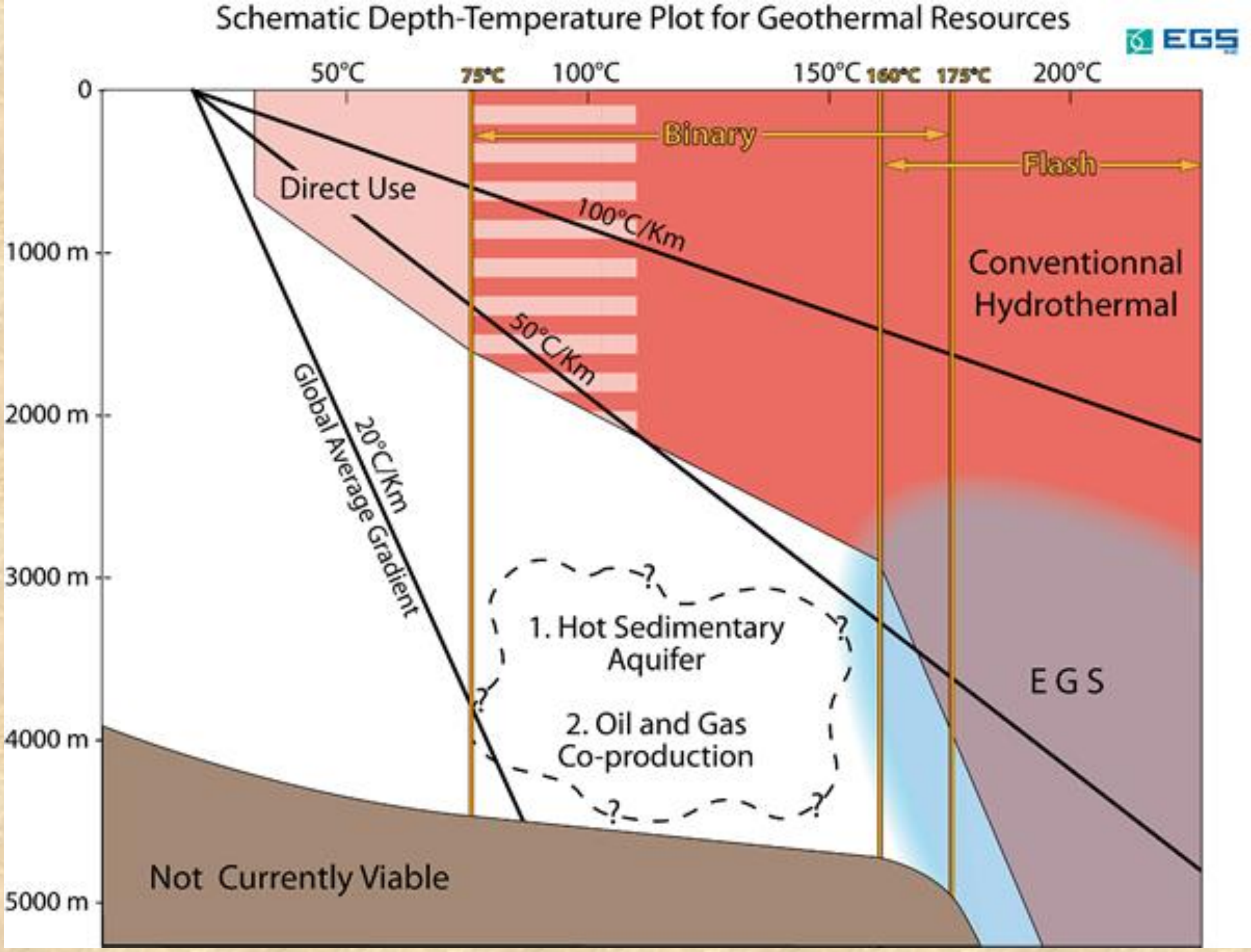

U.S. Renewable Energy Supply
(quadrillion Btu)
11
9
7
5
3
1
projections
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
Solar
Geothermal
Other biomass
Wind power
Liquid biofuels
Wood biomass
Hydropower

Geothermal Energy

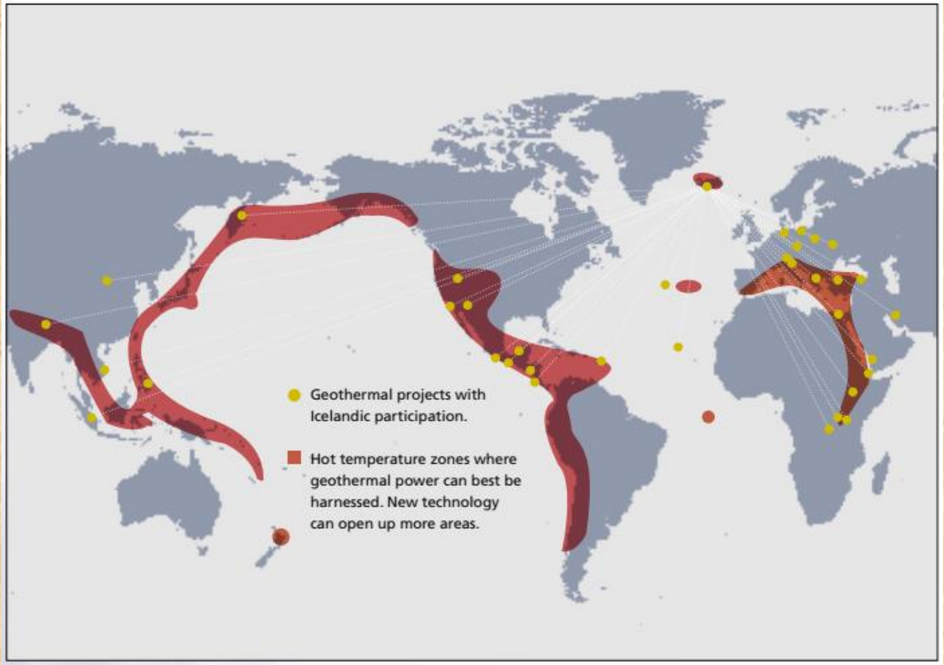


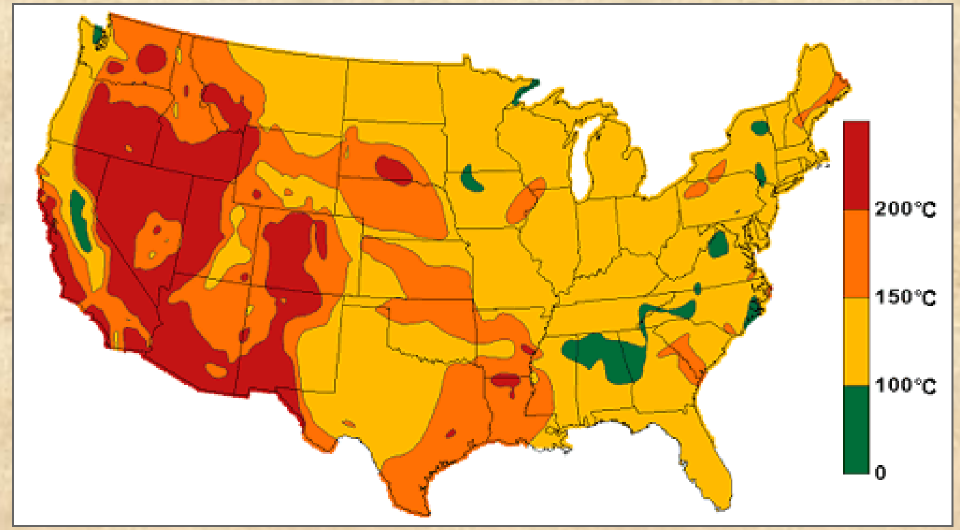





Schematic Depth-Temperature Plot for Geothermal Resources
EGS
50°C
75°C
100°C
150°C
160°C
175°C
200°C
0
1000 m
2000 m
3000 m
4000 m
5000 m
Binary
Flash
Direct Use
100°C/Km
50°C/Km
20°C/Km
Global Average Gradient
Conventionnal Hydrothermal
1. Hot Sedimentary Aquifer
2. Oil and Gas Co-production
E G S
Not Currently Viable

World Geothermal Sources

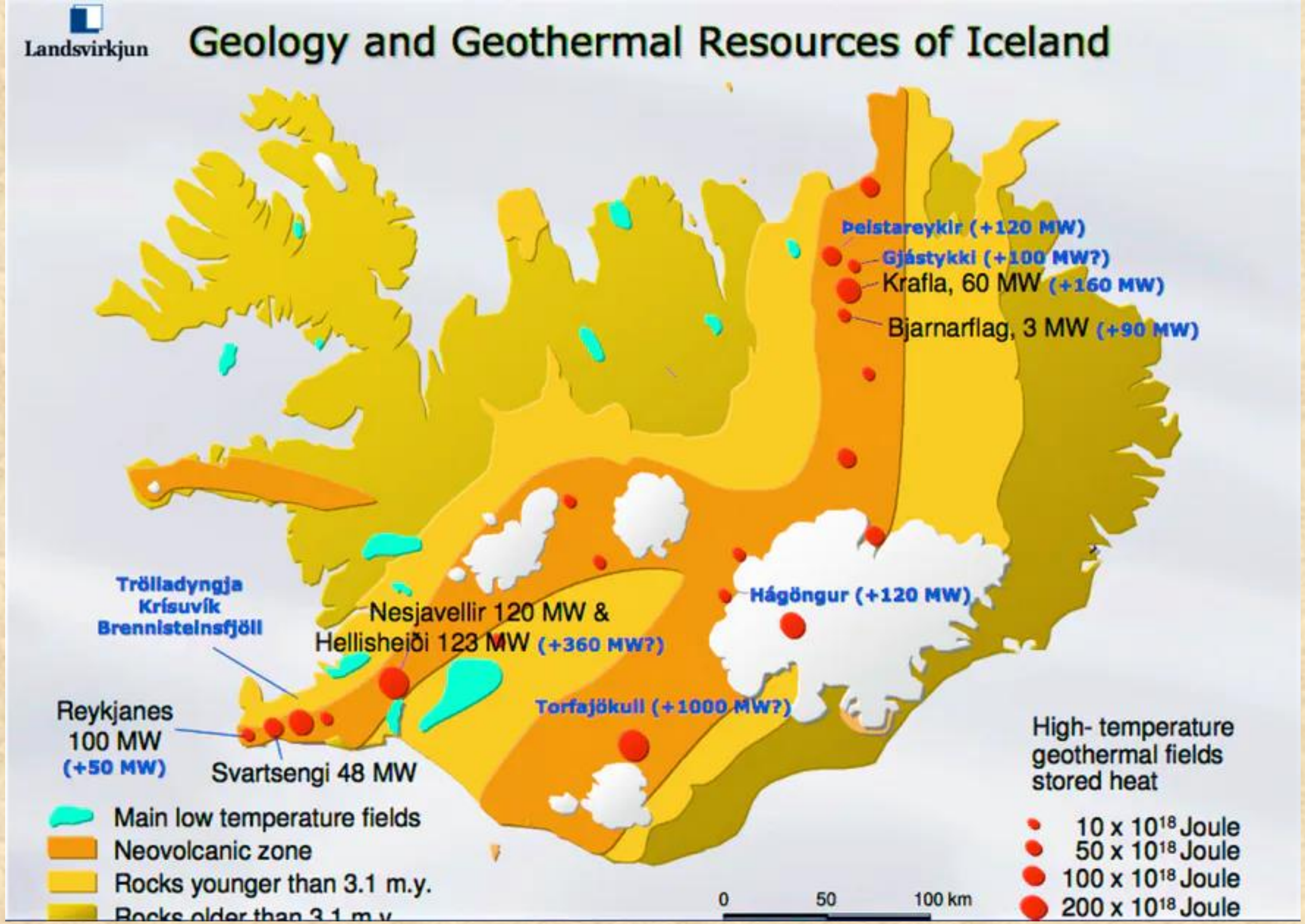




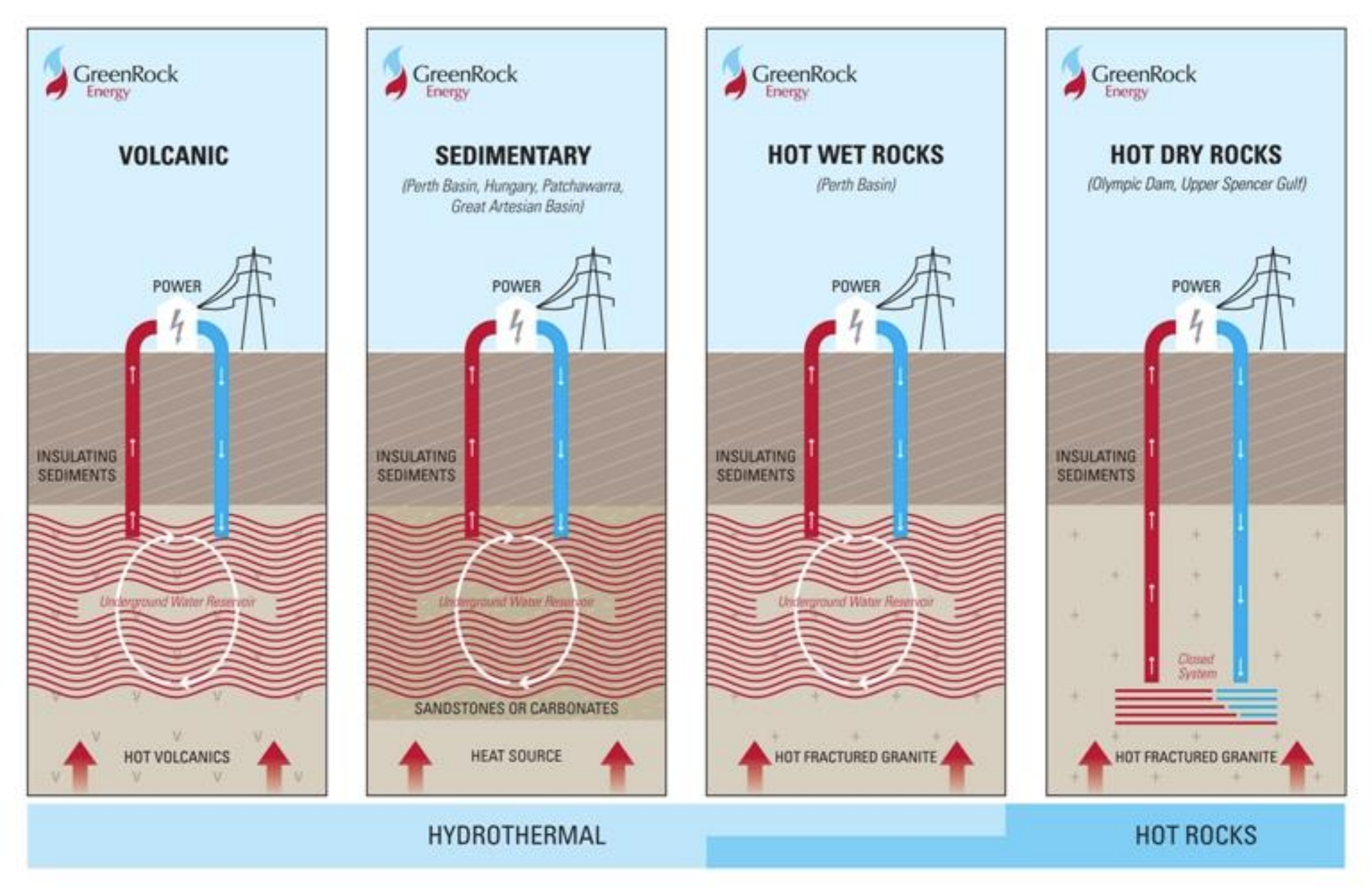
US Geothermal Sources

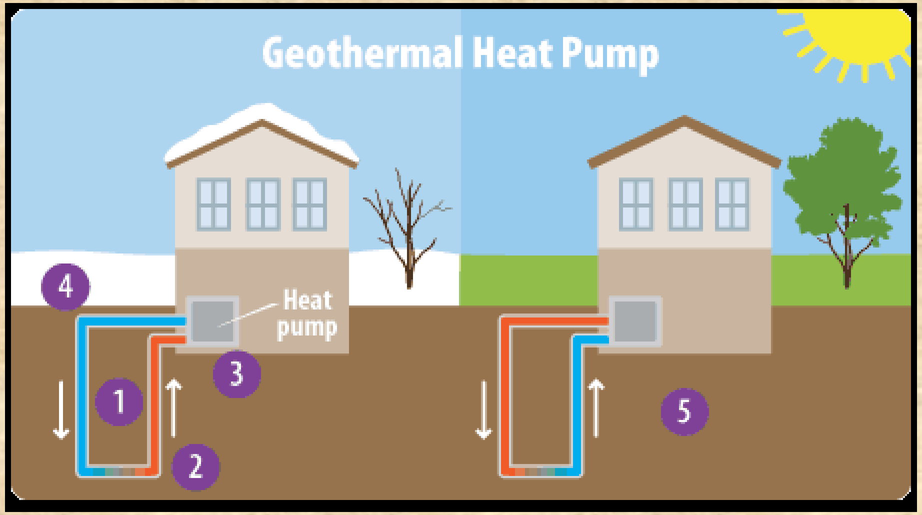
TABLE 8.1 | TOP GEOTHERMAL ELECTRICITY–PRODUCING COUNTRIES

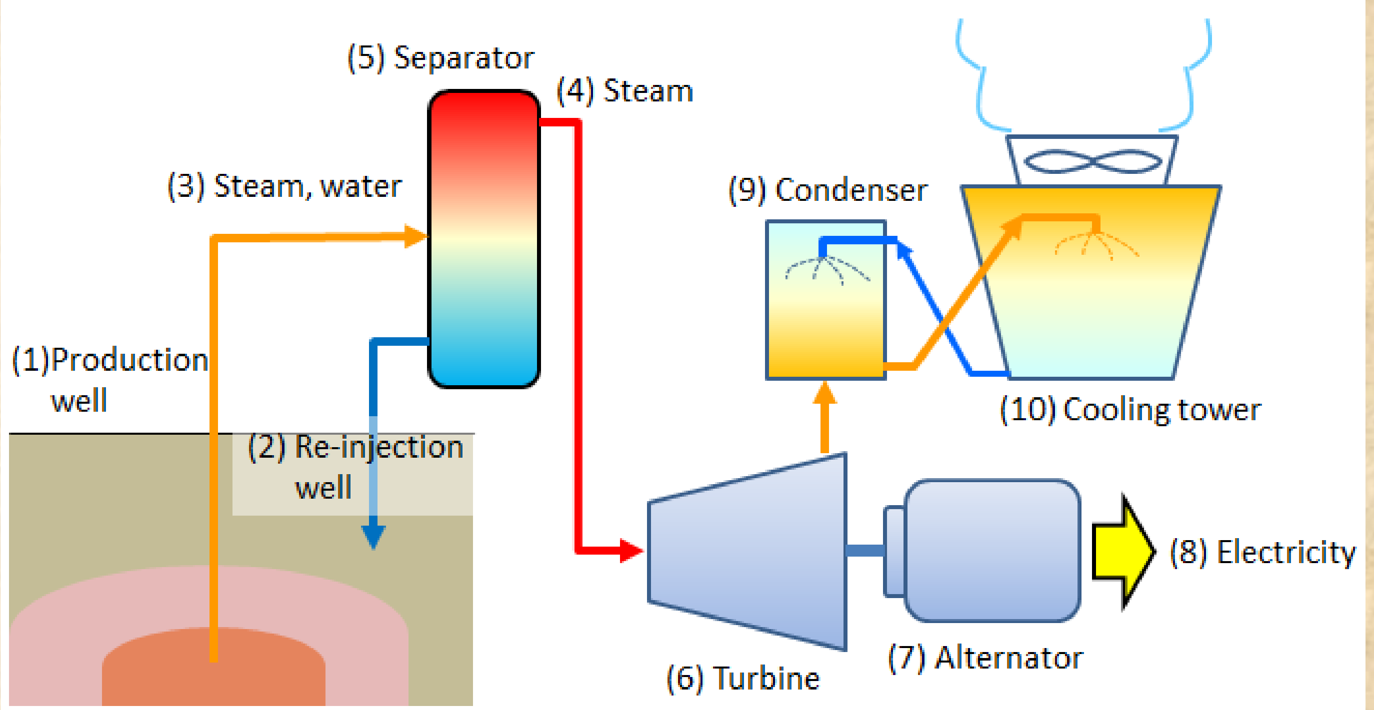
Country	Percentage of electricity from geothermal resources	Annual geothermal electricity generation (TWh)
Kenya	47	2.9
Iceland	32	5.2
New Zealand	18	7.0
Costa Rica	18	1.5
Philippines	17	9.6
California	6.1	12
Indonesia	4.9	9.6
Mexico	2.6	6.1
Italy	2.0	5.7
Turkey	1.6	3.2
United States	0.4	17
Japan	0.3	2.7
World	0.4	74


Landsvirkjun
Geology and Geothermal Resources of Iceland
Þeistareykir (+120 MW)
Gjástykki (+100 MW?)
Krafla, 60 MW (+160 MW)
Bjarnarflag, 3 MW (+90 MW)
Hágöngur (+120 MW)
Trölladyngja
Krísuvík
Brennisteinsfjöll
Nesjavellir 120 MW &
Hellisheiði 123 MW (+360 MW?)
Torfajökull (+1000 MW?)
Reykjanes
100 MW
(+50 MW)
Svartsengi 48 MW
Main low temperature fields
Neovolcanic zone
Rocks younger than 3.1 m.y.
0 50 100 km
High- temperature
geothermal fields
stored heat
10 x 10^18 Joule
50 x 10^18 Joule
100 x 10^18 Joule
200 x 10^18 Joule

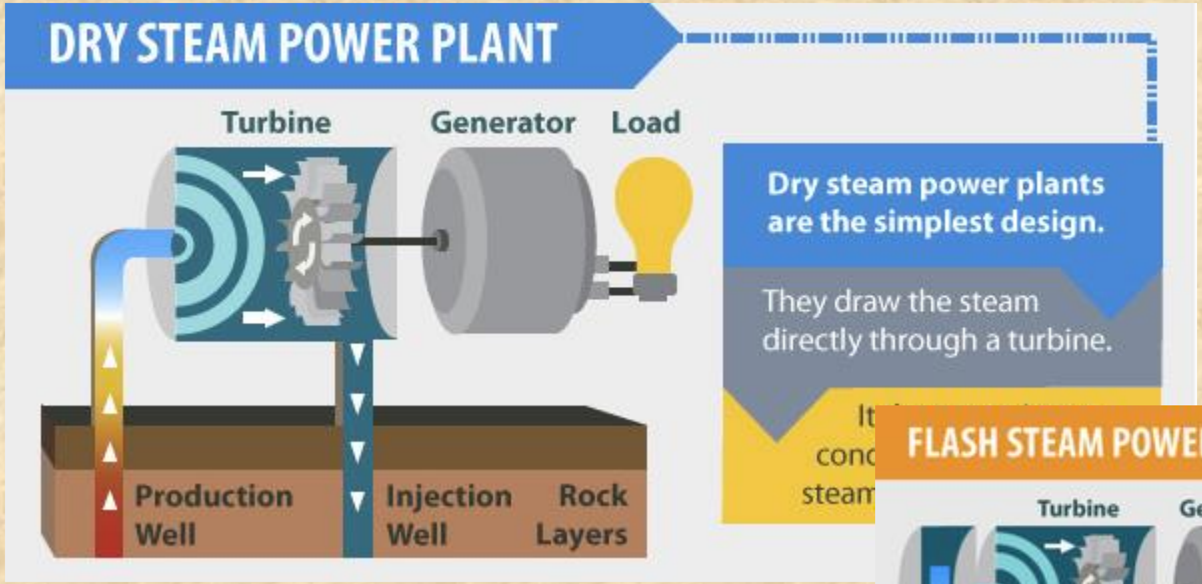
Types of Geothermal Energy Systems

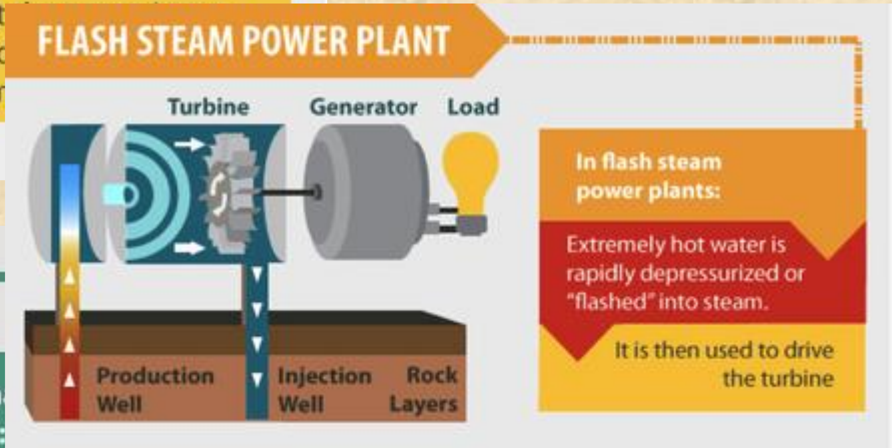


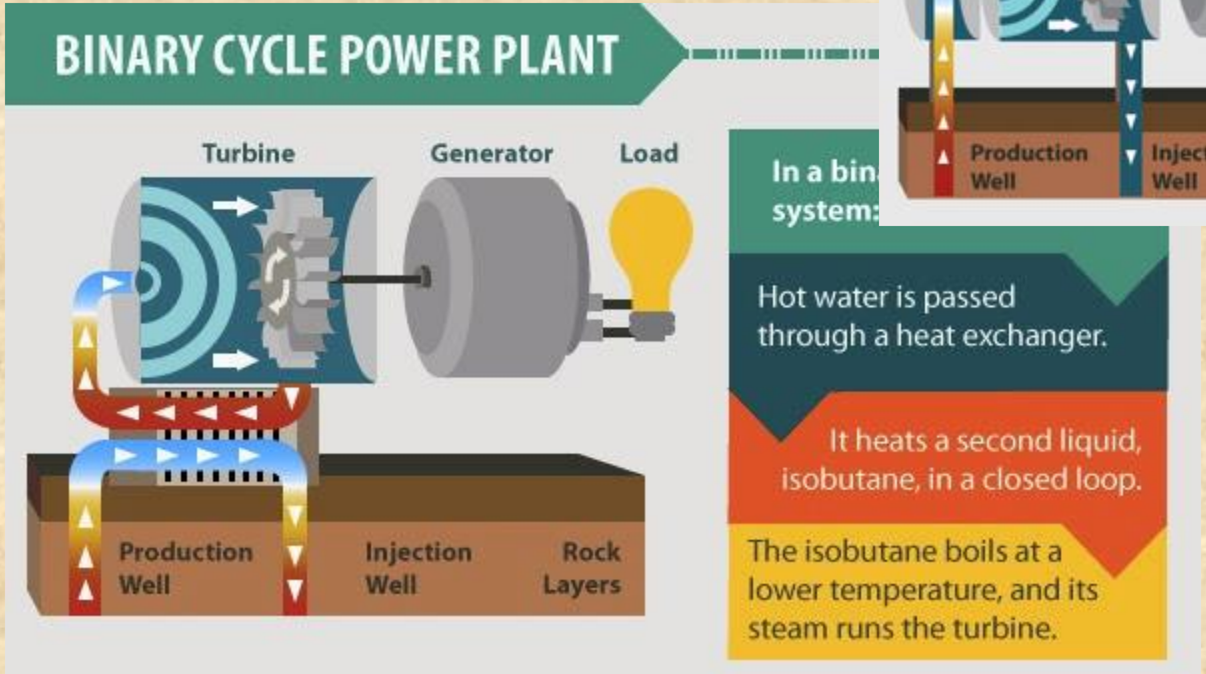

Geothermal Heat Pump
Heat pump
1
2
3
4
5


(5) Separator
(4) Steam
(3) Steam, water
(9) Condenser
(1)Production well
(2) Re-injection well
(10) Cooling tower
(8) Electricity
(6) Turbine
(7) Alternator

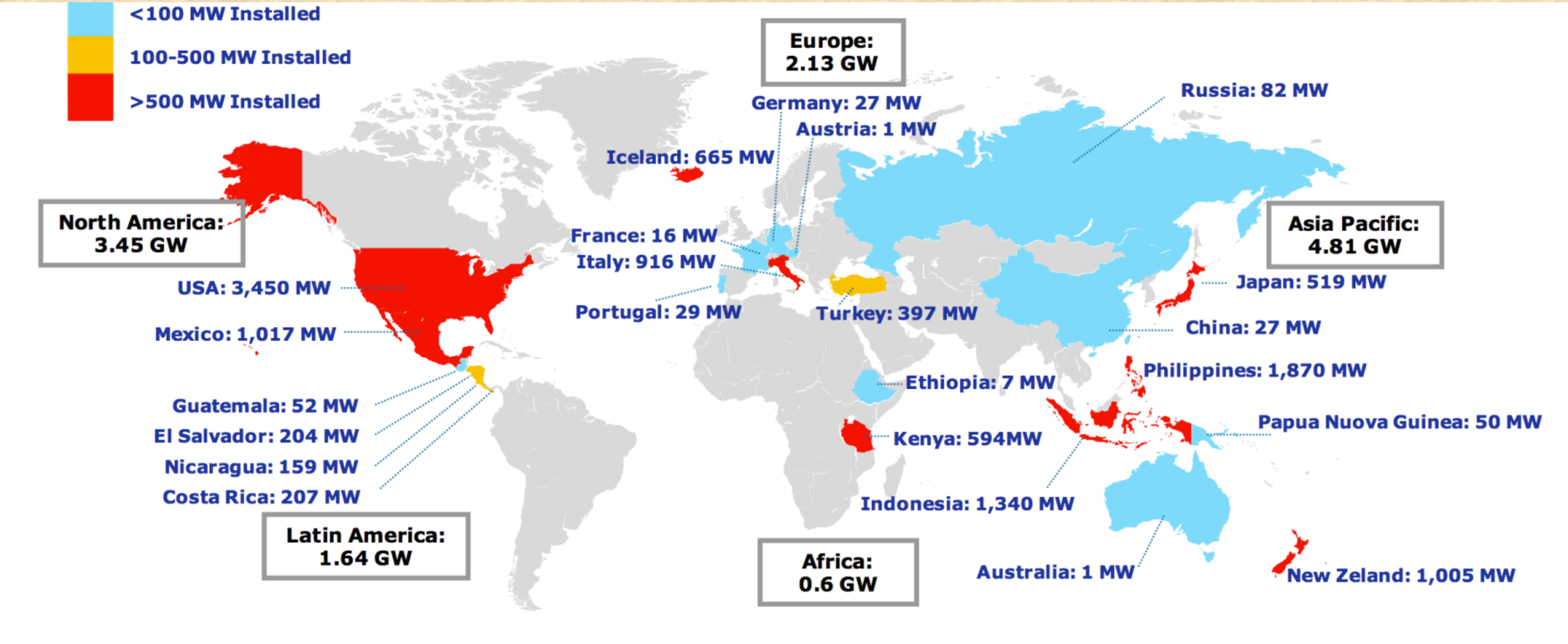
Types of Geothermal Power Plants







Current World Geothermal Power Generation

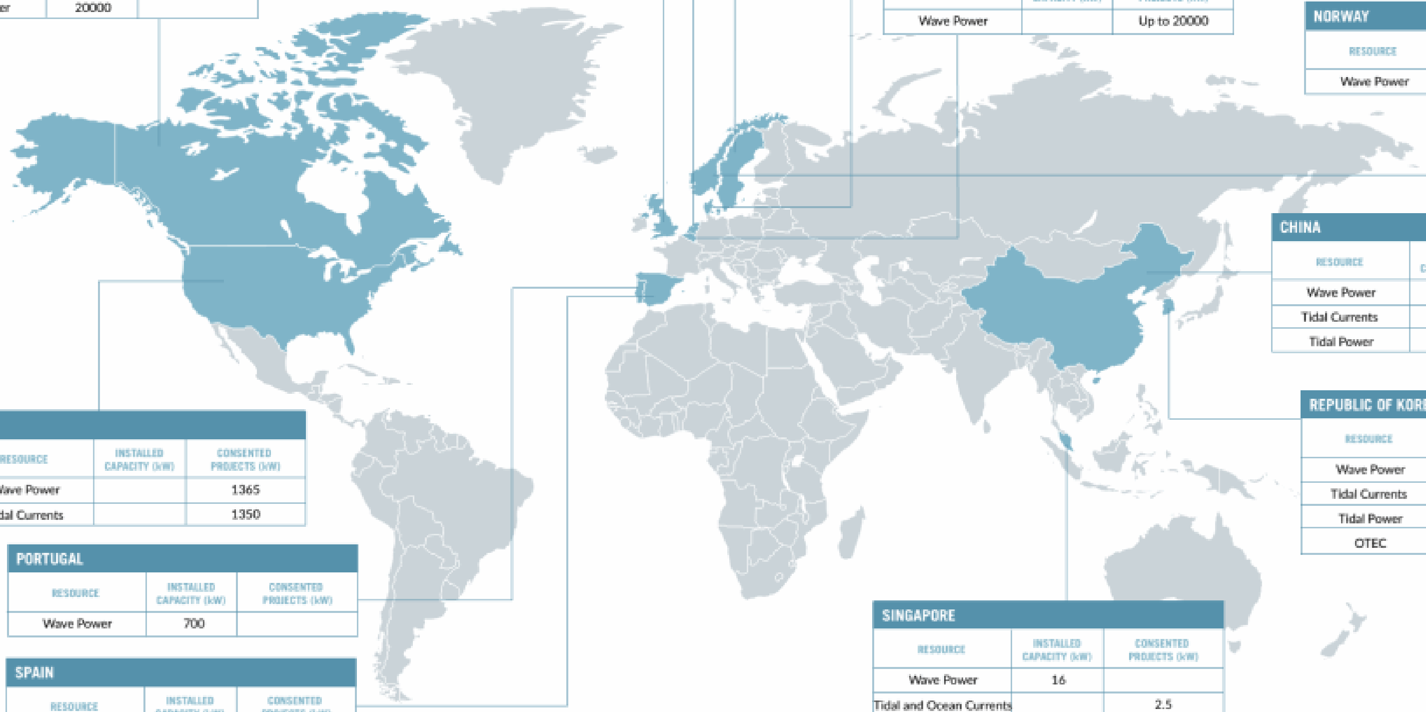


To put the above numbers into perspective, recall that Seabrook nuclear plant is a 1000 MW plant and for Massachusetts there was ~1200 MW of coal-fired power plant capacity.

Environmental impact

- The thermal efficiency of geothermal electric plants is low, around 10-23%
- Fluids drawn from the deep earth carry a mixture of gases, $\mathbf{CO_2}$, $\mathbf{H_2S}$, $\mathbf{CH_4}$ **and** $\mathbf{NH_3}$. These contribute to **global warming and noxious smells if released.**
- Hot water from geothermal sources may hold in **solution trace amounts of toxic chemicals, such as mercury, arsenic, boron, antimony, and salt.**
- Plant construction can adversely affect **land stability**.
- Enhanced geothermal systems can trigger **earthquakes** as part of hydraulic fracturing.
- **Capital costs** tend to be high.
- **Drilling accounts for over half the costs** and **exploration of deep** resources entails significant risks.
- Subsidence

Ocean power utilization and potential



NETHERLANDS

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power		
Tidal Currents	130	3000
Salinity Gradient	50	

UK

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power	3730	40000
Tidal Currents	5600	96000

CANADA

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Tidal Currents		20450
Tidal Power	20000	

USA

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power		1365
Tidal Currents		1350

PORTUGAL

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power	700	

SPAIN

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power	296	300

SWEDEN

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power	180	10400-10600
Tidal and Ocean Currents	7.5	

DENMARK

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power		115

BELGIUM

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power		Up to 20000

NORWAY

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power	200	

CHINA

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power	350	2860
Tidal Currents	170	4500
Tidal Power	3900	200

REPUBLIC OF KOREA

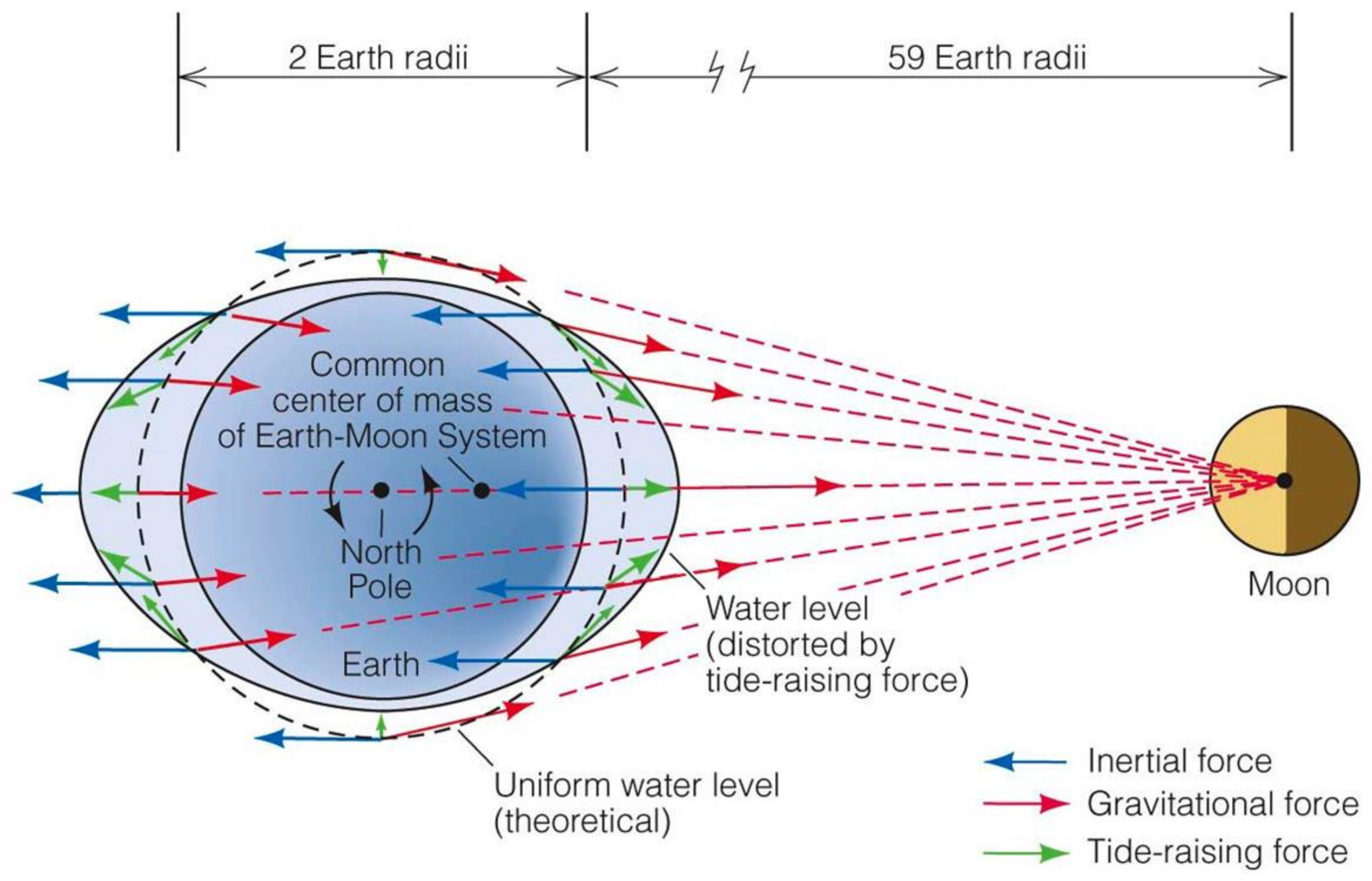
RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power	500	300
Tidal Currents	1000	1300
Tidal Power	1000	1300
OTEC	220	1000

SINGAPORE

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power	16	
Tidal and Ocean Currents		2.5

Annapolis Tidal Power Generating Station, Nova Scotia

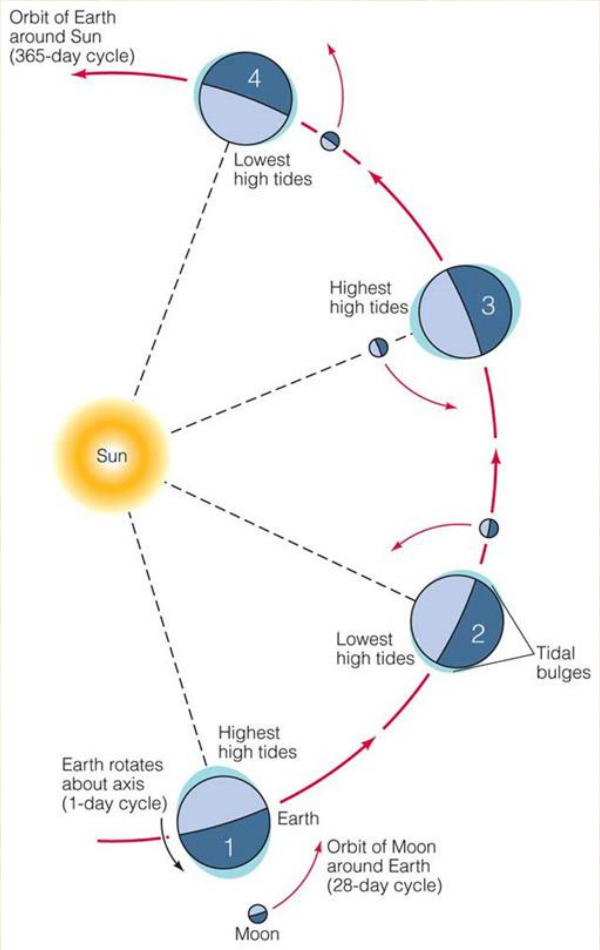
Equilibrium Tidal Theory – Earth Uniformly Covered with Water

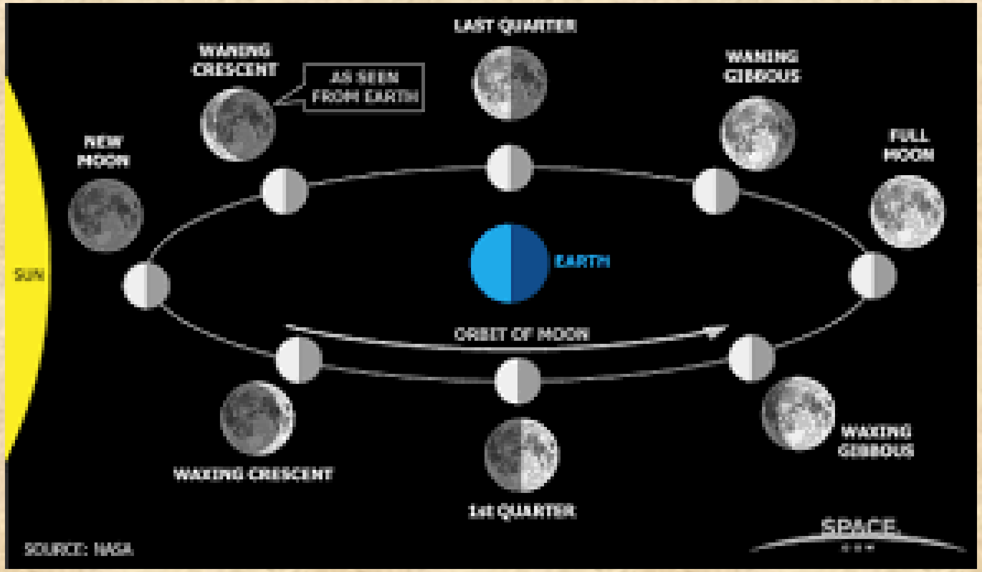


Spring and Neap Tides

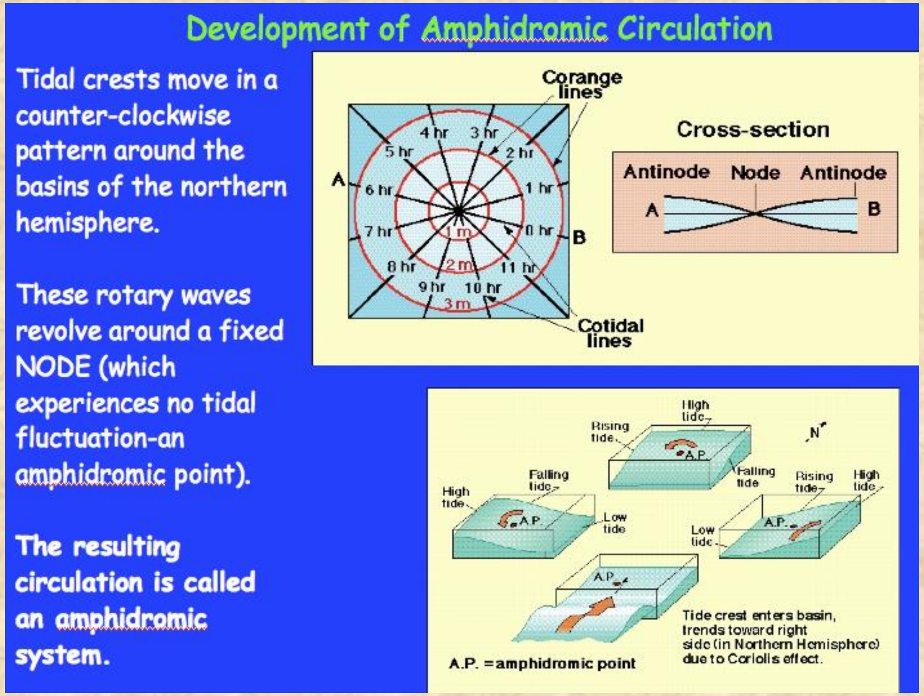
Phases of the Moon

Diurnal vs Semi-diurnal tides





Dynamical Tidal Theory



- **Corange circles are lines connecting points which experience the same tidal range.**
  - *The lines form irregular circles which are concentric about the node.*
  - *Tidal range increases outward from the node.*
- **Amphidromic systems rotate clockwise in the southern hemisphere and counterclockwise in the northern hemisphere because of the difference in the direction of Coriolis deflection.**
- **Irregular coastlines distort the rotary motion.**
- **Actual tide expressed at any location is a composite of 65 different tidal components.**

Small-Amplitude Wave Theory (4)

- Gravity waves may be classified by the water depth in which they travel. The classifications are made according to the magnitude of d/L and the resulting limiting values taken by the function tanh(kd):

classification	d/L	kd	tanh(kd)
Deep water	> 1/2	> π	≈1
Transitional	1/25 to 1/2	1/4 to π	tanh(kd)
Shallow water	< 1/25	< 1/4	≈kd

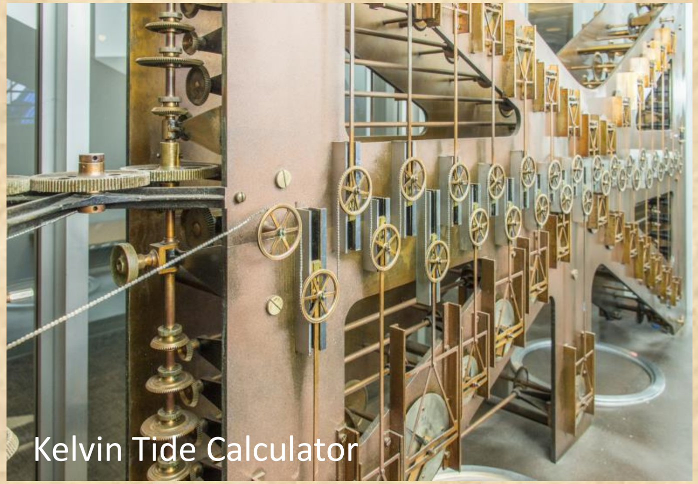
- In deep water, tanh(kd) approaches unity, Eqs. (2) and (3) reduce to

$$C_0 = \sqrt{\frac{gL_0}{2\pi}} = \frac{L_0}{T} = \frac{g}{\omega} \qquad (4)$$

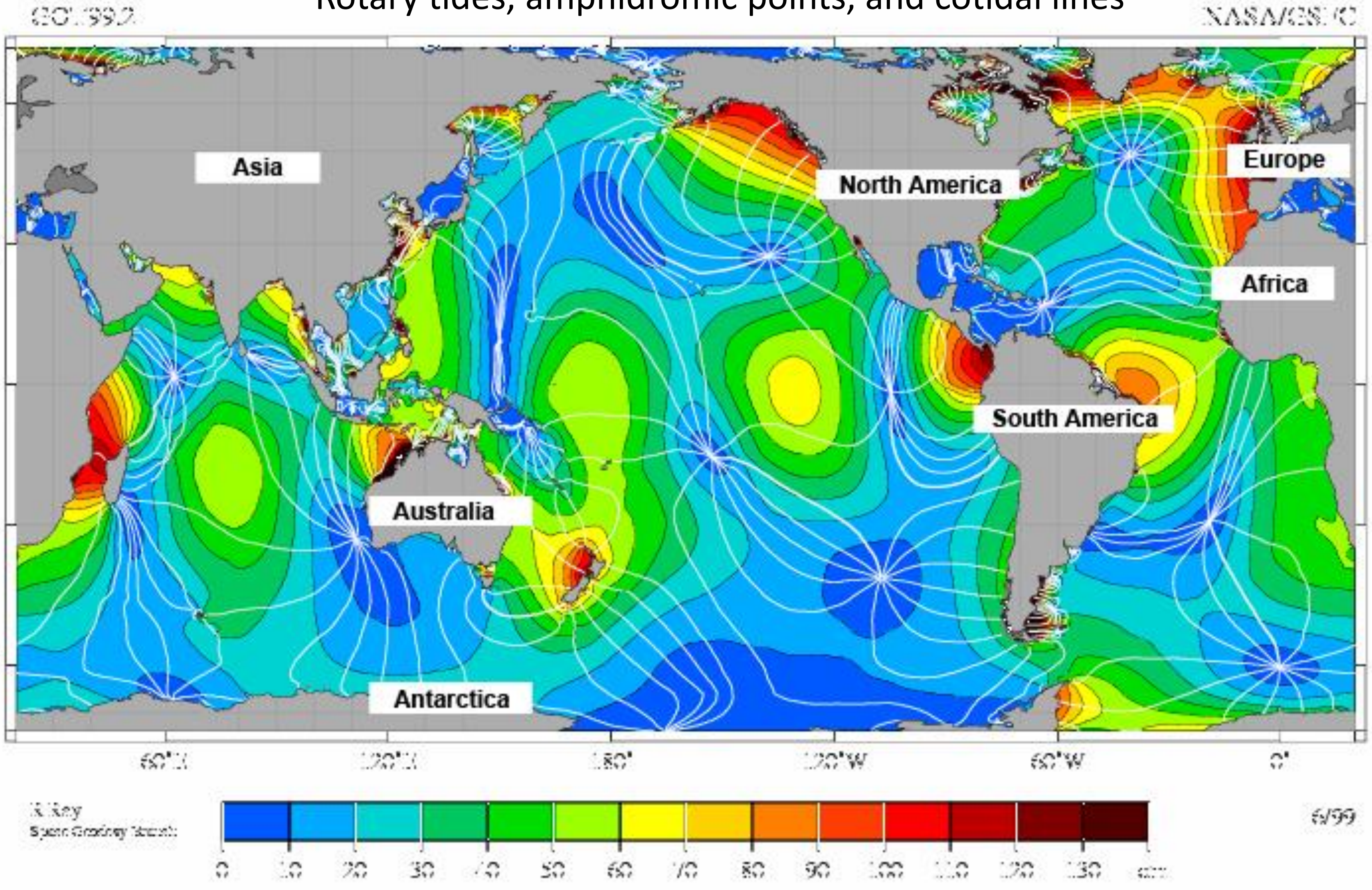
- When the relative water depth becomes shallow, Eq.(2) can be simplified to

$$C_0 = \sqrt{gd} \qquad (5)$$

Tides are shallow water waves.


Kelvin Tide Calculator

Rotary tides, amphidromic points, and cotidal lines



Natural Period of Standing Waves

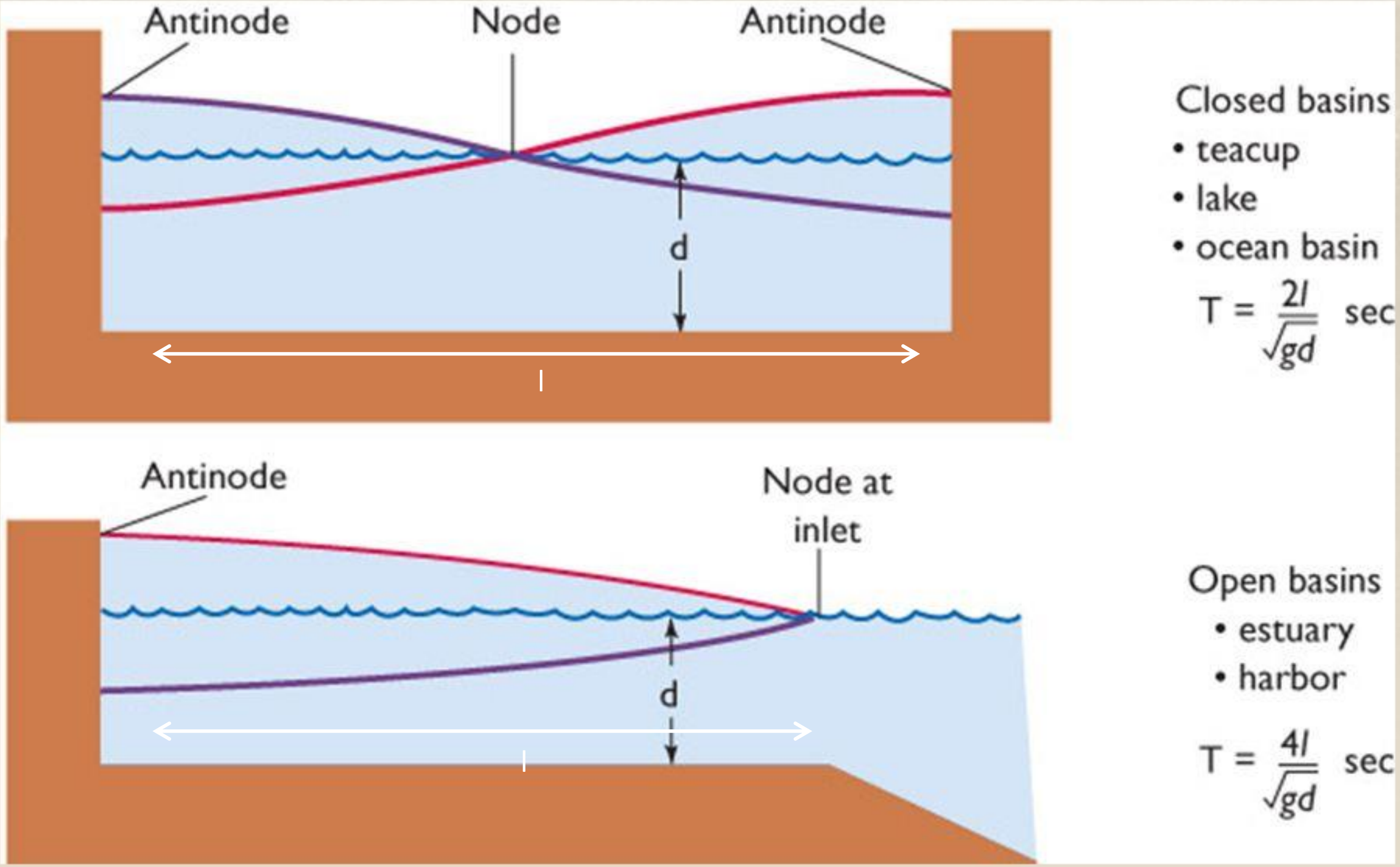
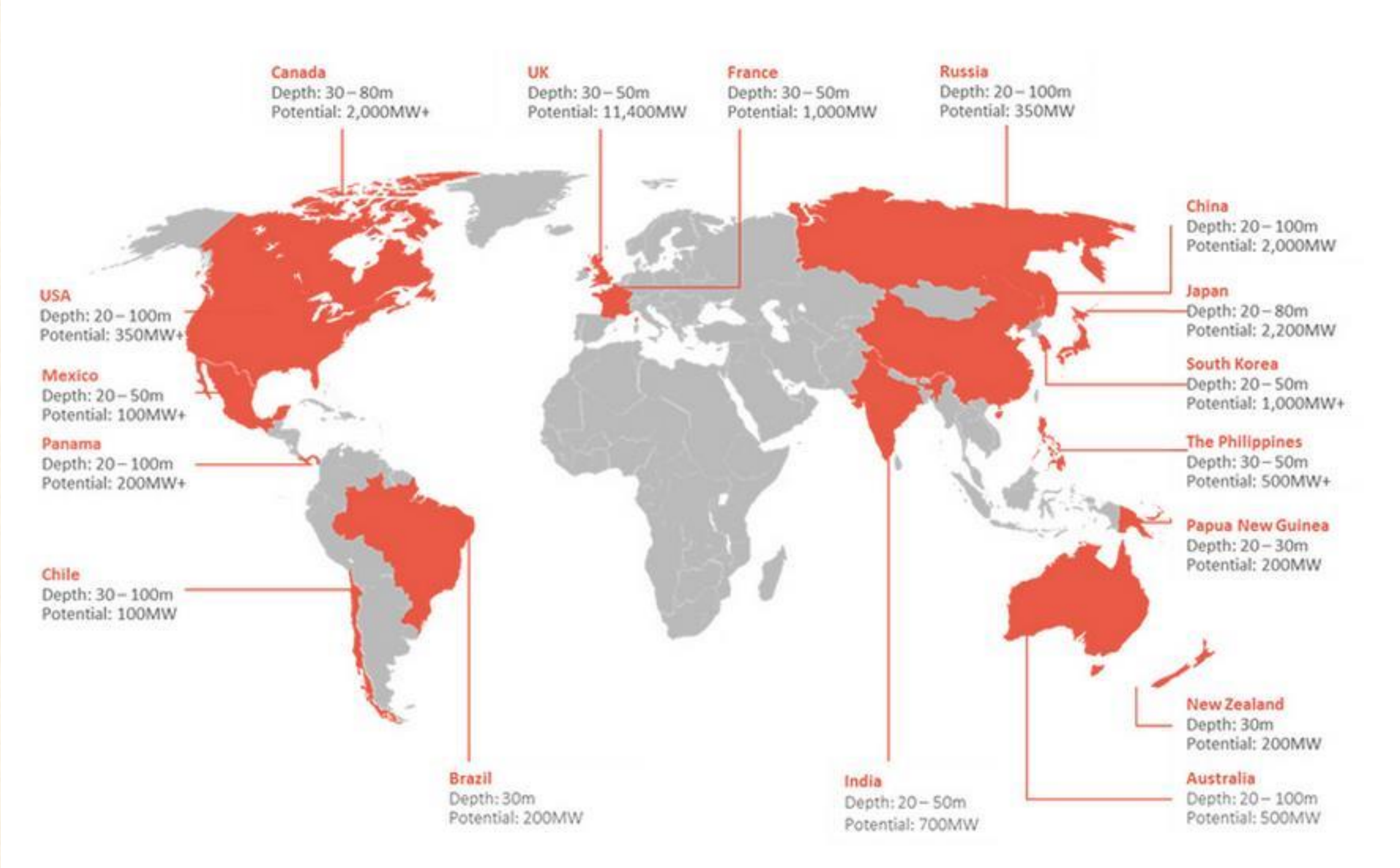


Figure 7-11 Natural Period of Standing Waves

Potential Tidal Energy



Tidal Barrage Energy Calculations

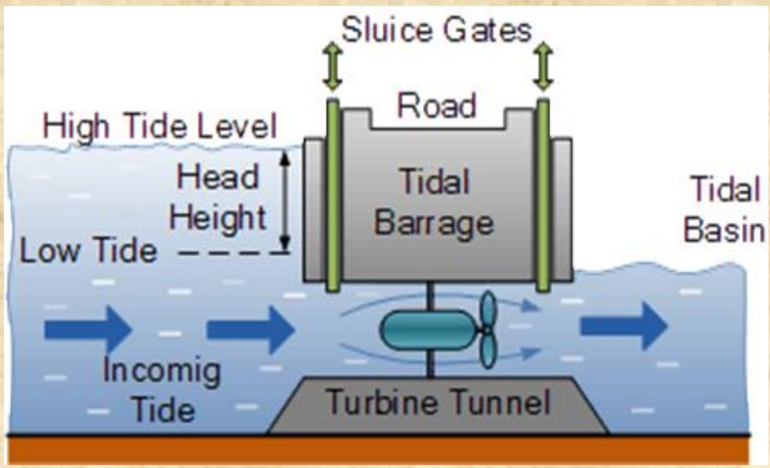
R = range (height) of tide (in m)
A = area of tidal pool (in km^2)
m = mass of water
$g = 9.81\ m/s^2$ = gravitational constant
$\rho = 1025\ kg/m^3$ = density of seawater
$\eta \cong 0.33$ = capacity factor (20-35%)

$$E = \eta mgR/2 = \eta(\rho AR)gR/2$$

$$E = 1397\eta R^2 A \quad \text{kWh per tidal cycle}$$

Assuming 706 tidal cycles per year (12 hrs 24 min per cycle)

$$E_{yr} = 0.997 \times 10^6 \eta R^2 A$$

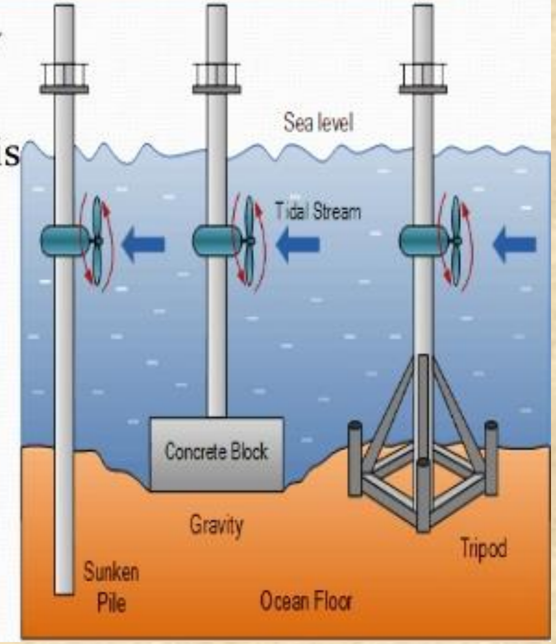


TIDAL STREAM GENERATORS:-

- It make use of kinetic energy of moving water.
- The power taken by turbine is given by

$$P=(\rho C_p A V^3)/2$$

- It's design is similar to wind turbines but it's performance is better.



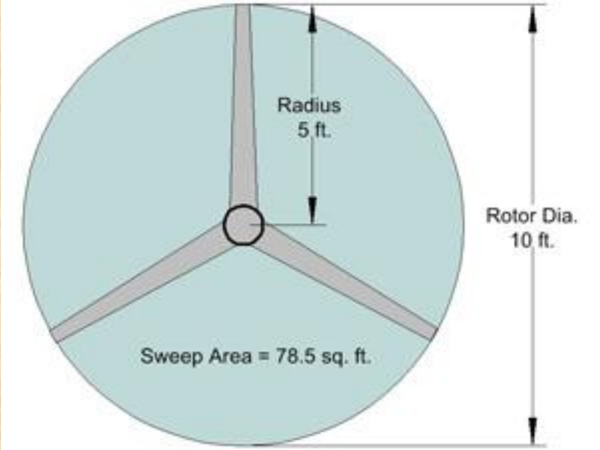
P = power generated (Watts)

C_P = turbine efficiency

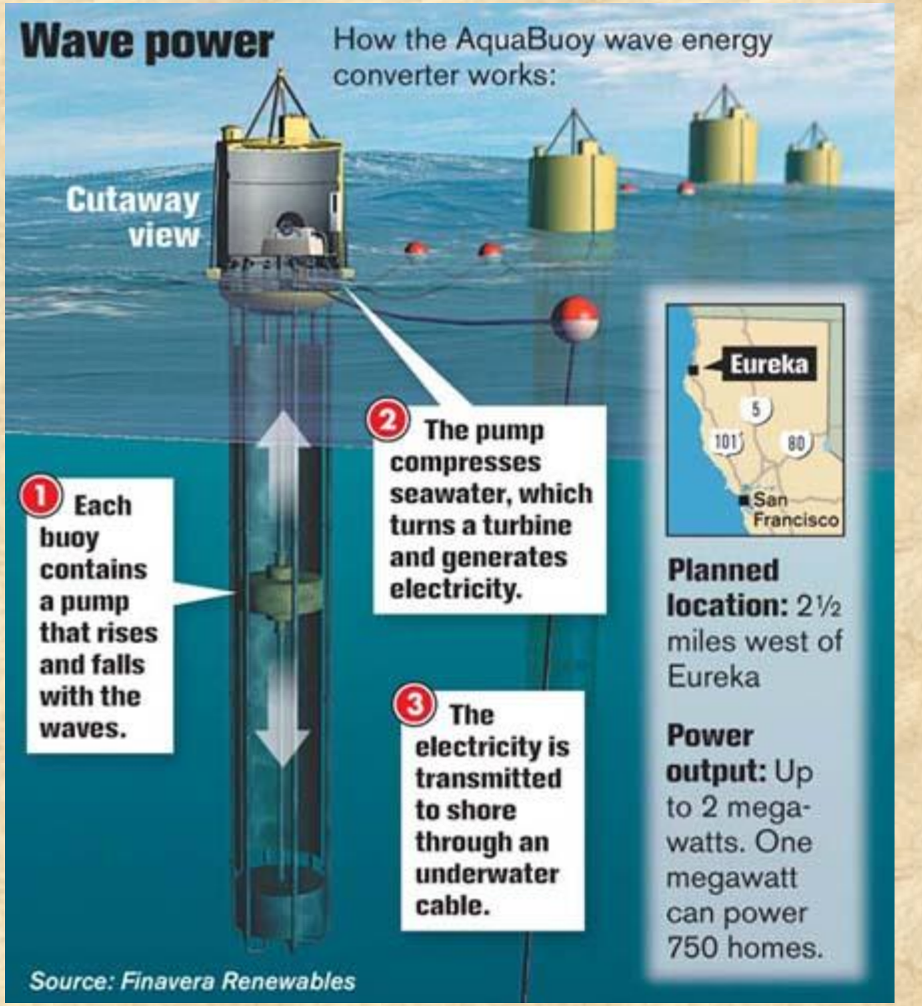
ρ = density of seawater (1025 kg/m^3

A = sweep area of the turbine (m^2)

V= velocity of the flow



Energy from Waves



Wave Power Calculations

H_s^2 = Significant wave height – 4x *rms* water elevation (m)
T_e = avg time between upward movements across mean (s)
P = Power in kW per meter of wave crest length

$$P = \frac{H_s^2 T_e}{2}$$

Example: $H_s^2 = 3\text{m}$ and $T_e = 10\text{s}$

$$P = \frac{H_s^2 T_e}{2} = \frac{3^2 \times 10}{2} = 45 \frac{kW}{m}$$