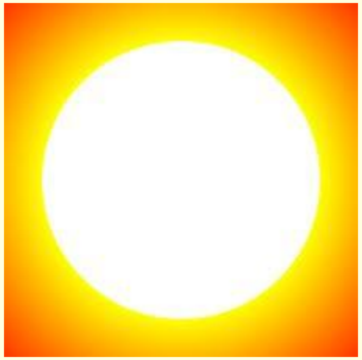
Renewable Energy Resources – an Overview



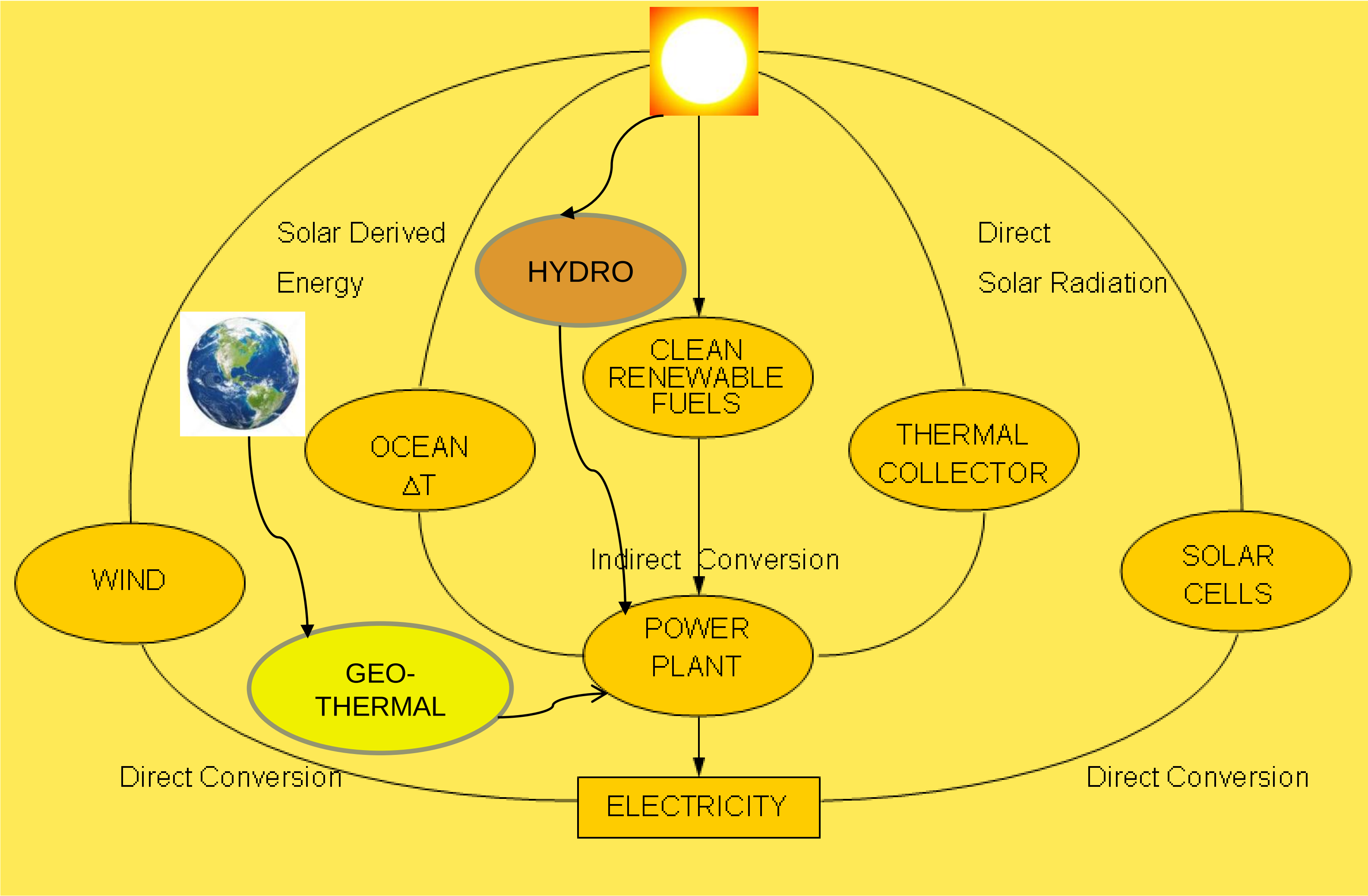
Y. Baghzouz

Professor of Electrical Engineering

Overview

- Solar-derived renewables
  - Photovoltaic (PV)
  - Concentrating Power Systems
  - Biomass
  - Ocean Power
  - Wind Power
  - Hydro Power
- Earth derived renewables
  - Geothermal

Electricity production from renewables



What is driving the fast growth?

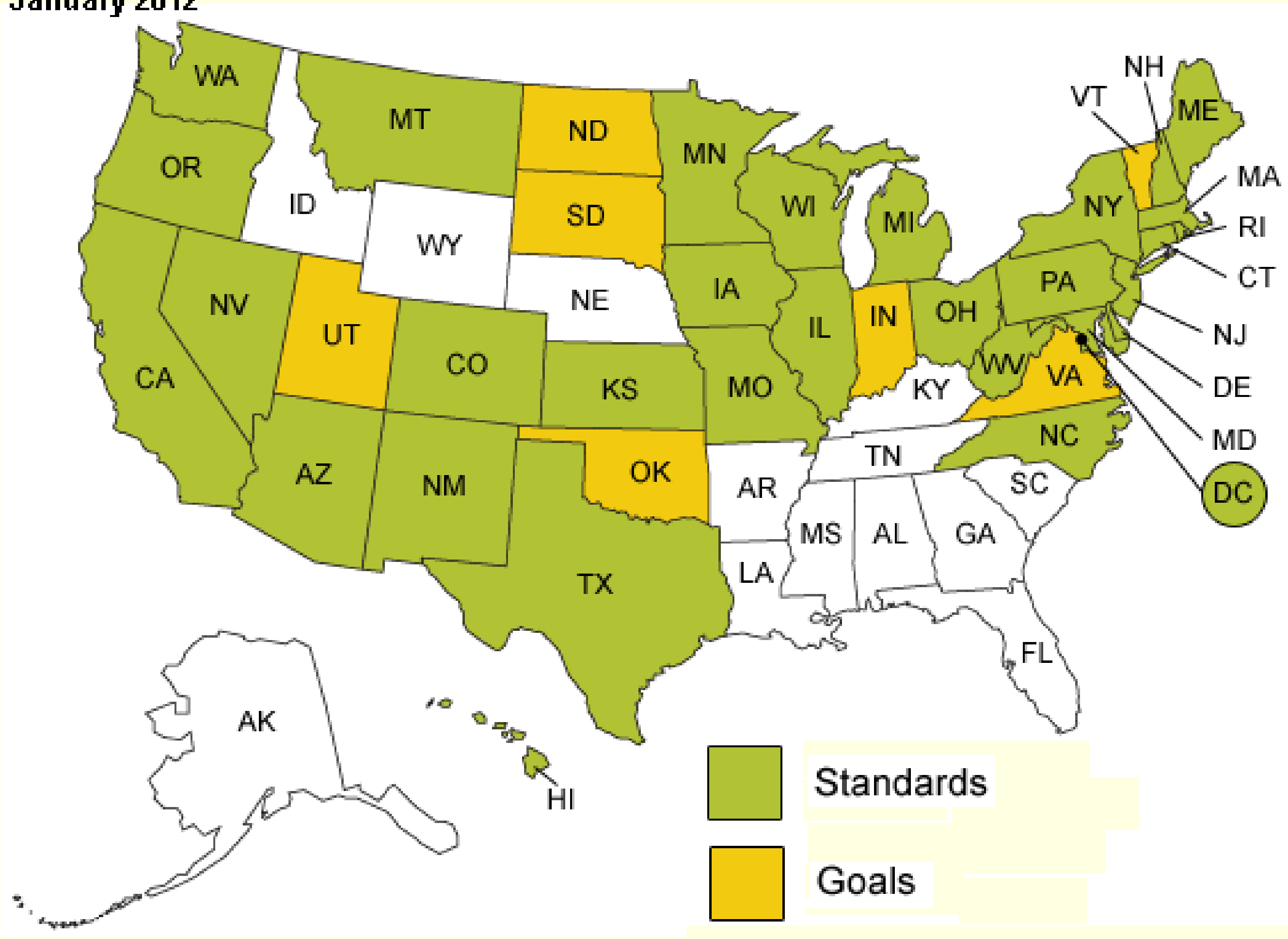
The growth in renewables over the past decade is driven mainly by the following:

- Global concern over the environment. Furthermore, fossil fuel resources are being drained.
- Renewable technologies are becoming more efficient and cost effective.
- The Renewable Electricity Production Tax Credit, a federal incentive, encourages the installation of renewable energy generation systems.
- Many countries have Renewable Portfolio Standards (RPS), which require electricity providers to generate or acquire a percentage of power generation from renewable resources.

US States with Renewable Energy Portfolio Standards.

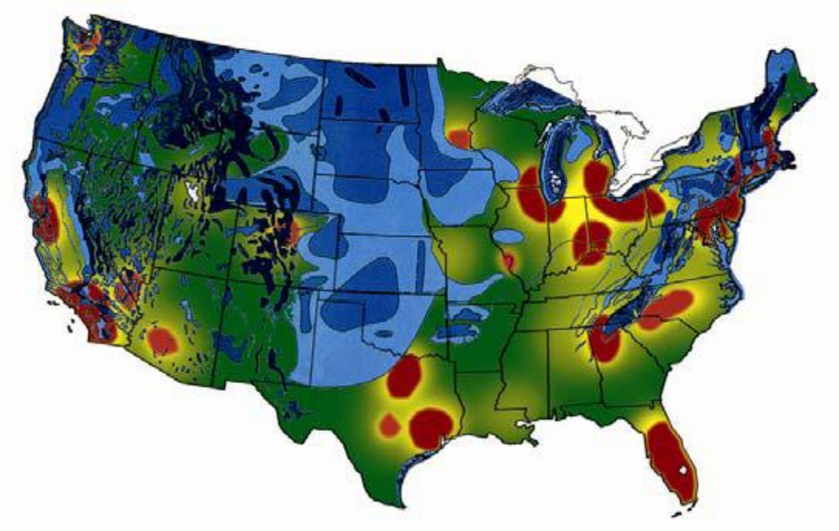
CA: 33% by 2020
NV: 25% by 2025
(EU: 20% by 2020)

States with Renewable Portfolio Standards (mandatory) or Goals (voluntary), January 2012



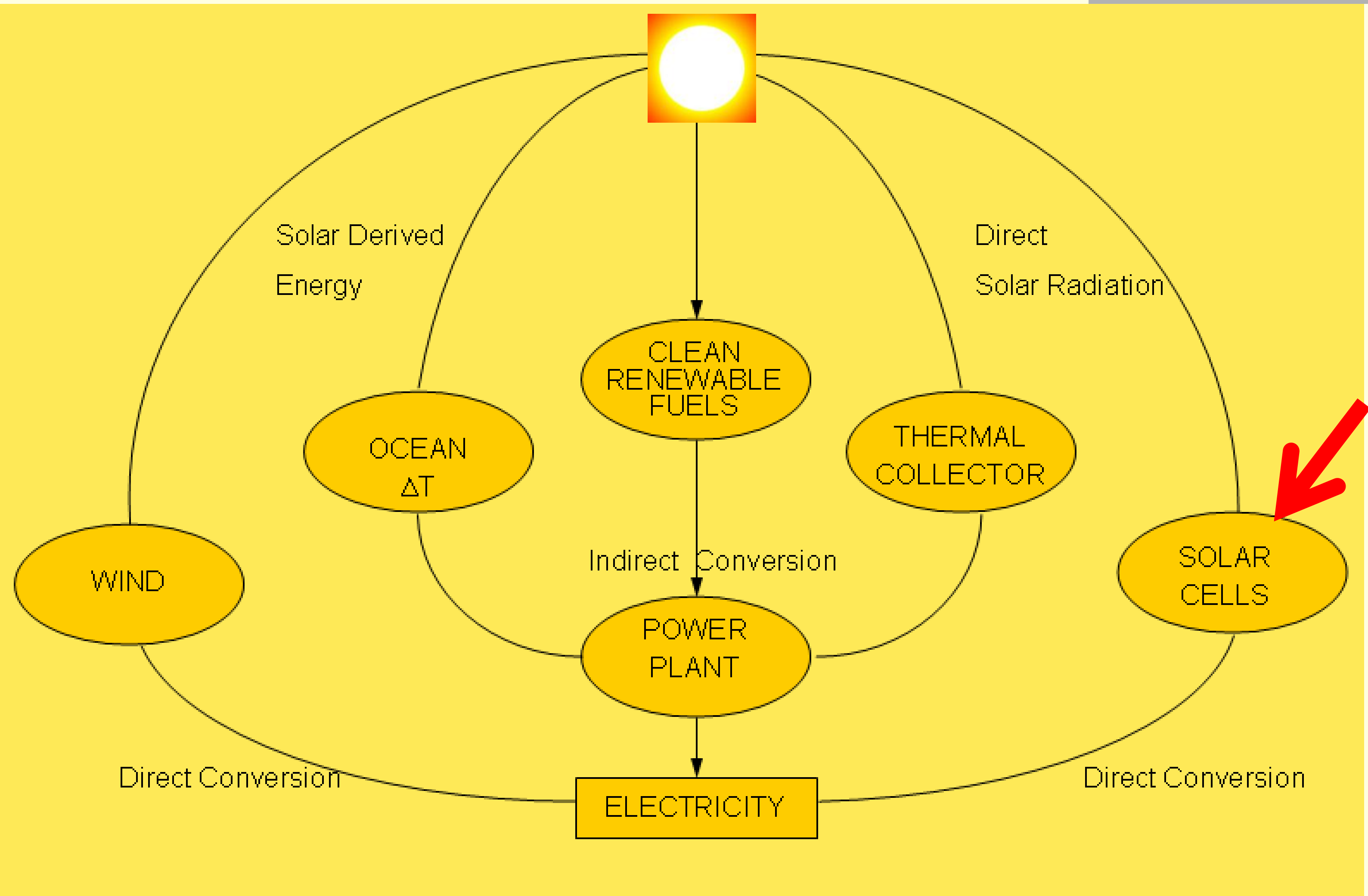
Why not produce more renewable energy?

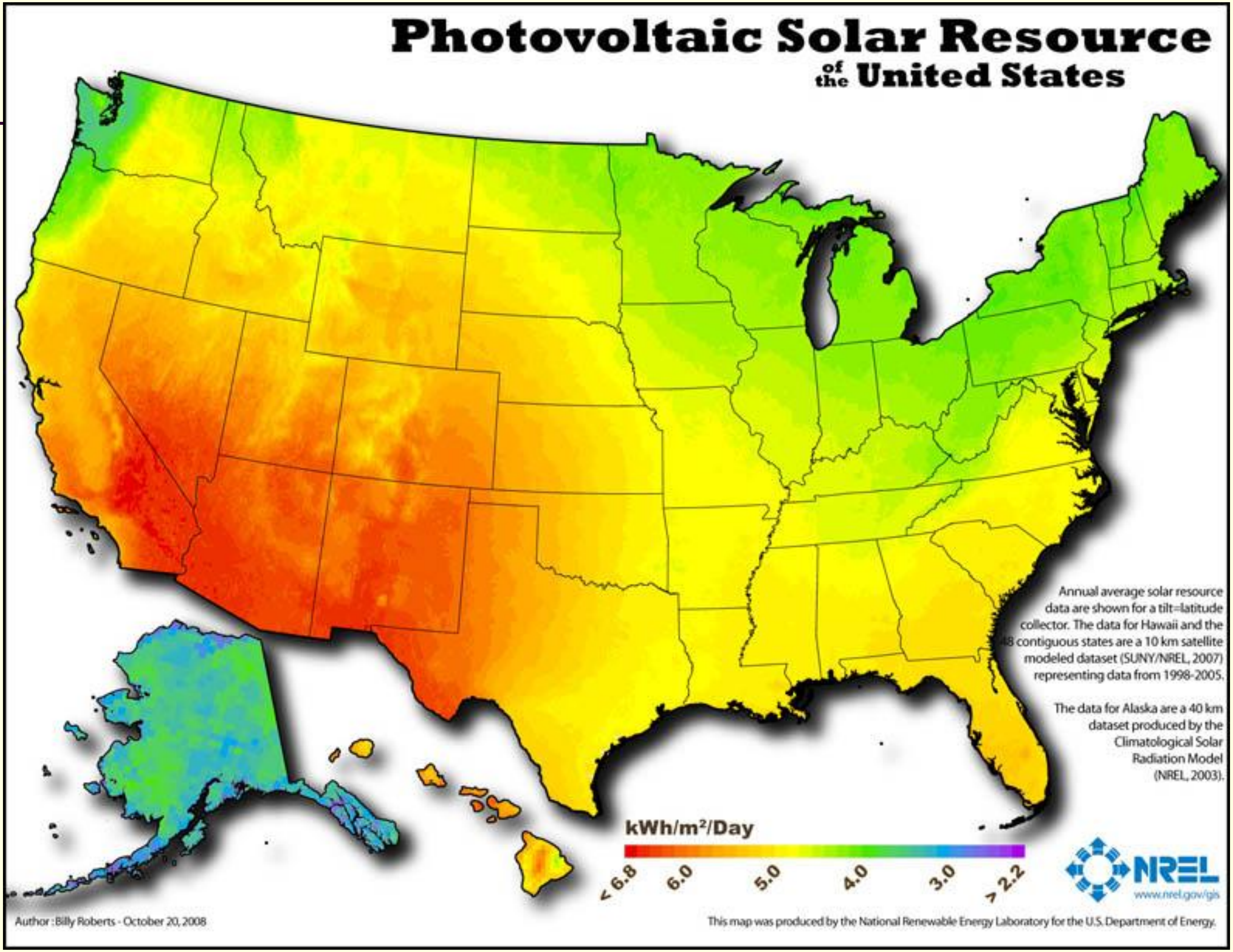
- **Renewable Energy Technologies Are Capital-Intensive:** Renewable energy power plants are generally more expensive to build and to operate than coal and natural gas plants. Recently, however, some wind-generating plants have proven to be economically feasible in areas with good wind resources.
- **Renewable Resources Are Often Geographically Remote:** The best renewable resources are often available only in remote areas, so building transmission lines to deliver power to large metropolitan areas is expensive.



Wind Availability and Demand
Blue - high wind potential,
Brown - large demand centers, and
Green - little wind and smaller demand centers.

Electricity production from renewables: Photovoltaics

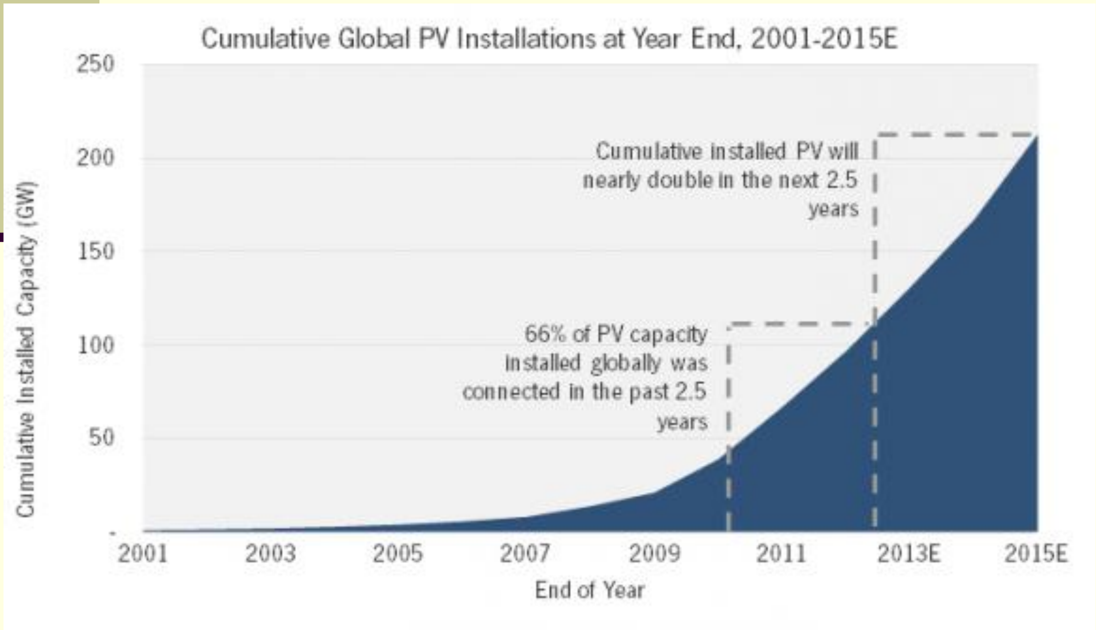




Photovoltaic Solar Resource
of the United States
Annual average solar resource data are shown for a tilt=latitude collector. The data for Hawaii and the 48 contiguous states are a 10 km satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998-2005.
The data for Alaska are a 40 km dataset produced by the Climatological Solar Radiation Model (NREL, 2003).
kWh/m²/Day
< 6.8
6.0
5.0
4.0
3.0
> 2.2
NREL
www.nrel.gov/gis
Author: Billy Roberts - October 20, 2008
This map was produced by the National Renewable Energy Laboratory for the U.S. Department of Energy.

Growth in Solar Photovoltaic

- The past decade has seen explosive growth in global solar photovoltaic installations.
- Countries with the most PV capacity in 2010-2012 (MWp) →



Total photovoltaic peak power capacity (MWp)[6

Country or Region	Total 2010	Total 2011[65]	Total 2012[66]
World	39,778	69,684	102,024
European Union	29,328	51,360	68,640
Germany	17,320	24,875	32,509[67]
Italy	3,502	12,764	16,987
China	893	3,093	8,043
United States	2,519	4,383	7,665
Japan	3,617	4,914	6,704
Spain	3,892	4,214	
France	1,025	2,831	3,843
Belgium	803	2,018	
Czech Republic	1,953	1,960	
Australia	504	1,298	2,291
United Kingdom	72	1,014	1,831
India	189	461	1,686
South Korea	662	754	

Largest PV systems to date

- Charanka Solar Park (India, 214 MW)
- Agua Caliente Solar Project (Yuma, AZ, 200 MW)
- Golmud Solar Park (China, 200 MW),
- Perovo Solar Park (Ukraine, 100 MW),
- Sarnia Photovoltaic Power Plant (Canada, 97 MW),
- Brandenburg-Briest Solarpark (Germany, 91 MW),
- Solarpark Finow Tower (Germany, 85 MW),
- Montalto di Castro Photovoltaic Power Station (Italy, 84 MW).
- A number of larger plants (in the 500 MW range) are under construction in CA, USA.

PV Installation Ranking (by State)

(Source: https://openpv.nrel.gov/rankings)

Rank By **Total Count** | Rank By **Avg. Cost $/W** | Rank By **Capacity MW**

Rank	State	Count	Cost $/W	Capacity (MW)
#1	CA	145631	7.08	2051.06
#2	AZ	19876	6.31	812.13
#3	NJ	18348	7.52	979.95
#4	MA	9795	6.10	244.78
#5	NY	6930	7.44	122.06
#6	TX	4391	5.83	133.57
#7	PA	4383	6.35	119.29
#8	MD	3712	6.92	89.89
#9	CT	2737	7.18	38.21
#10	CO	2607	5.83	130.45
#11	HI	2420	6.76	27.33
#12	OR	1943	5.74	46.41
#13	NM	1842	6.95	151.75
#14	VT	1630	6.76	27.55
#15	NV	1518	6.96	214.46

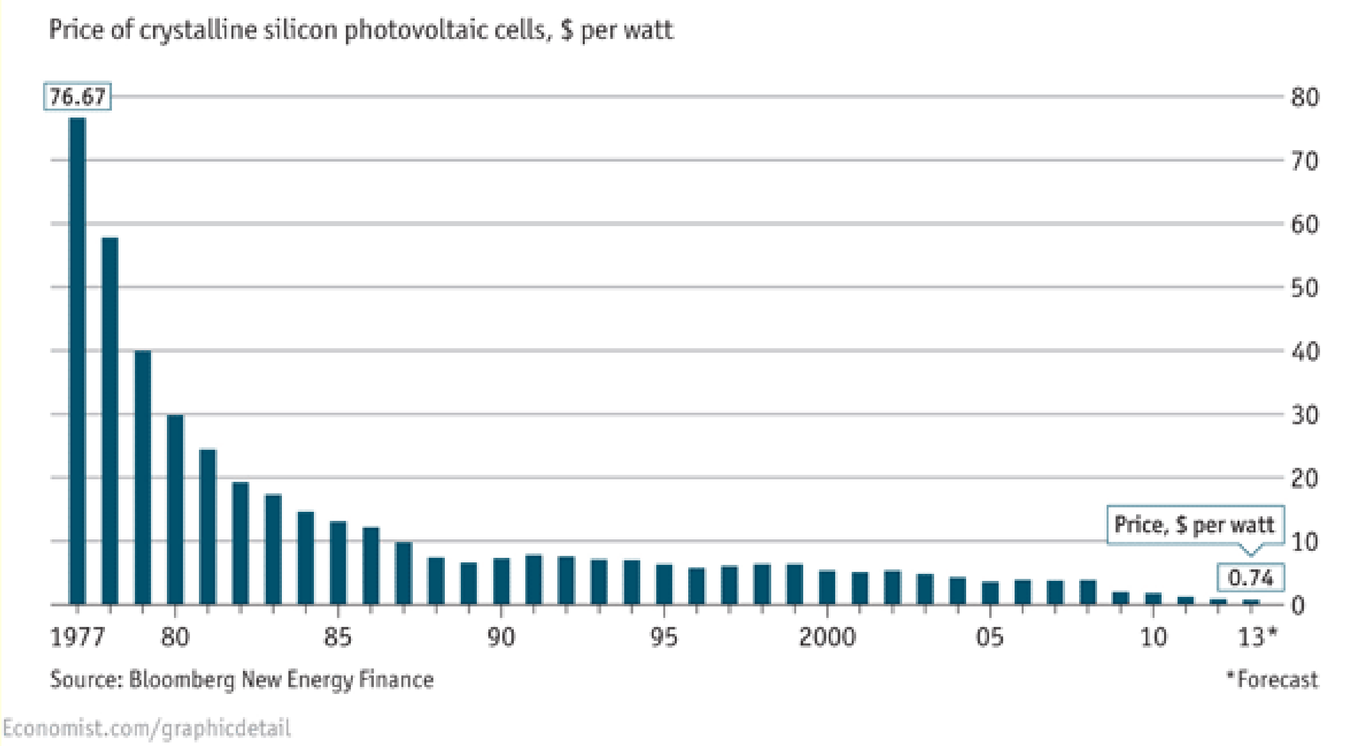
PV Plants in Nevada:

- 50 MW (Eldorado Valley), 50 MW (Prim)
- 15 MW (1-axis tracking) NAFB
- Numerous distributed PV systems (few kW – 350 kW)

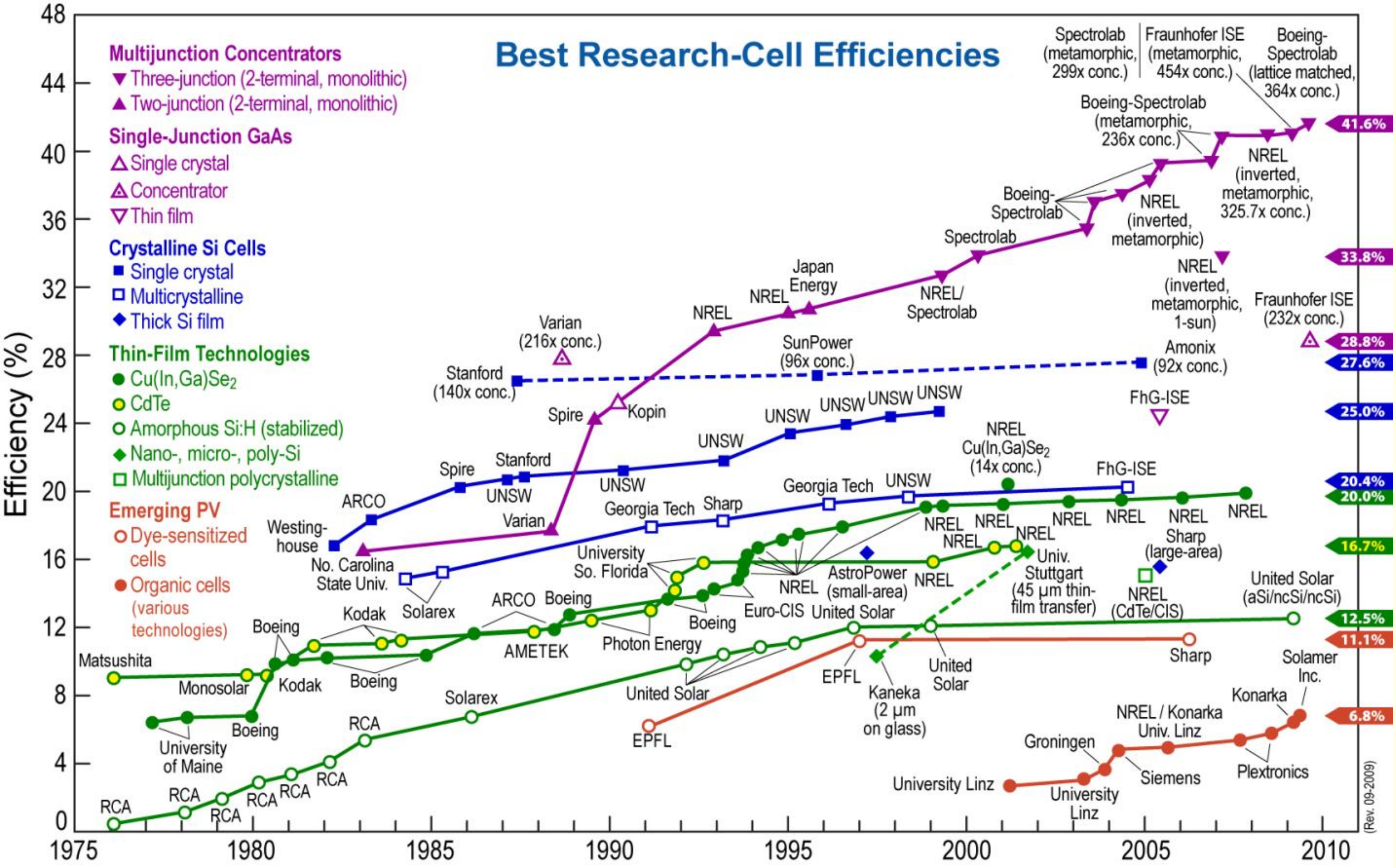




Trend of average PV price/watt (peak)

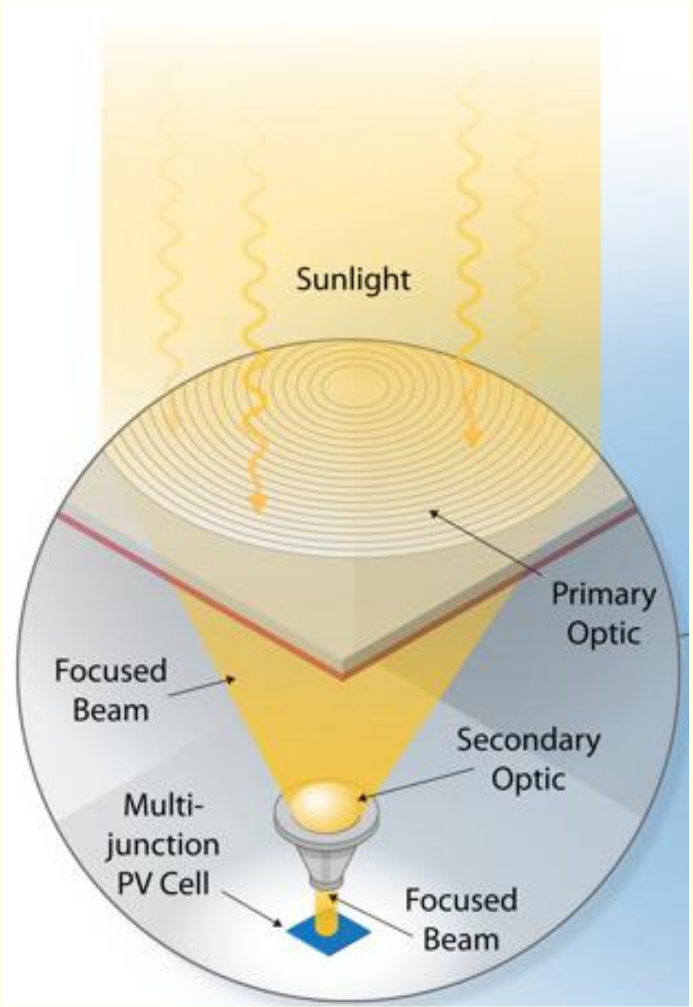


Trend of PV cell efficiencies

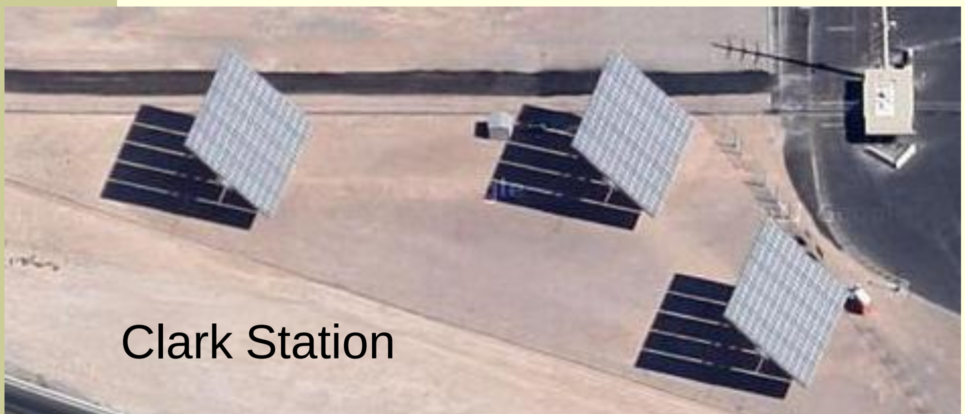


Concentrating PV cells

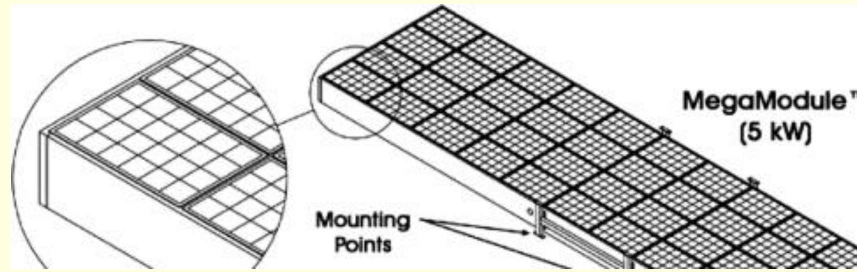
- One way to overcome the cost issue is to use these cells in a concentrator system, in which a relatively inexpensive lens is used to focus sunlight on just a small area of cells.
  - If a 10x10 cm lens focuses this area of incident sun onto a 0.5x0.5 cm cell, the concentration factor is 400. This cell with the lens can produce as much power as a 10-by-10-cm cell without a lens, but at nearly 0.25 % of the cell cost.



Concentrating PV Systems in Southern Nevada:



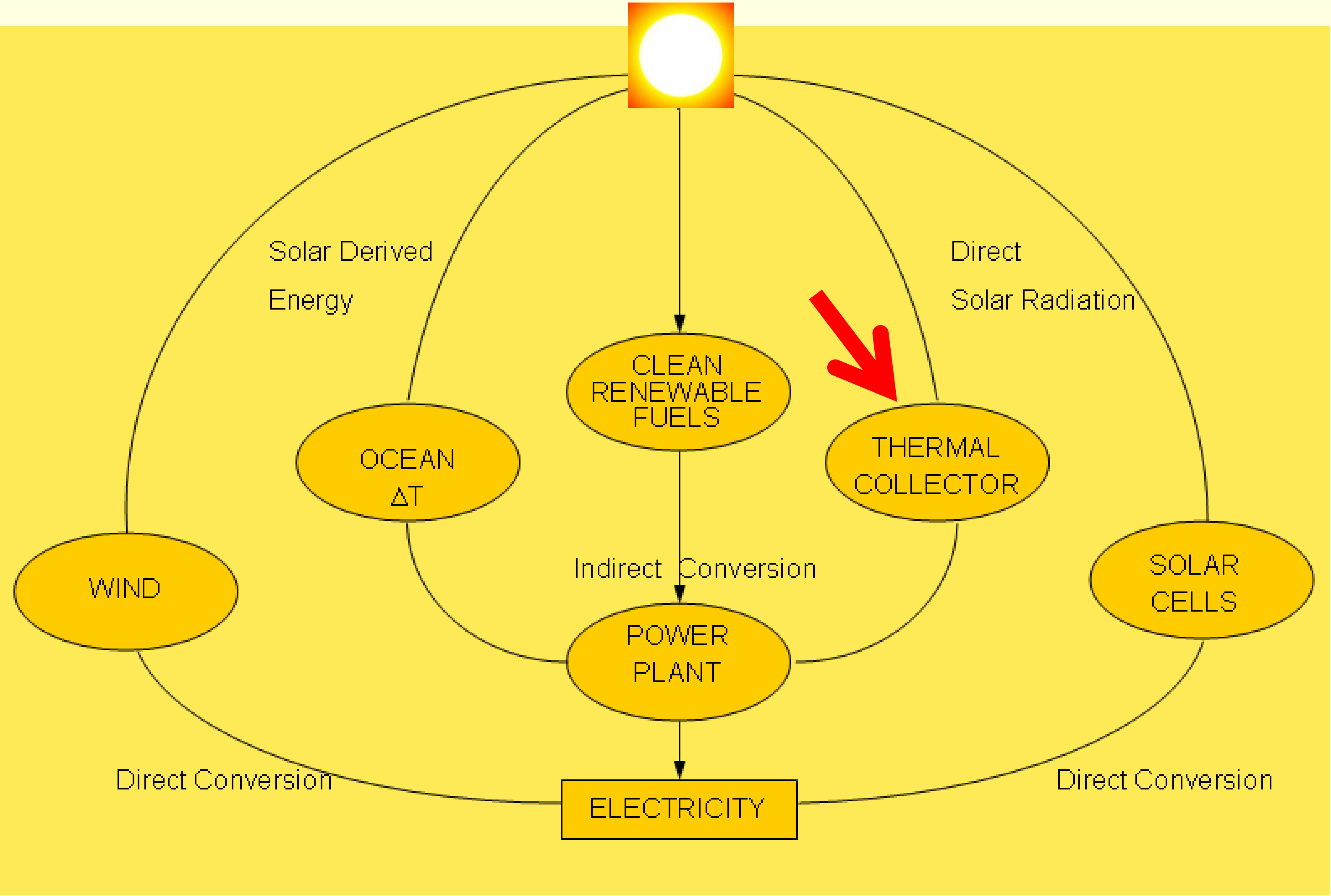
Clark Station



Concentrating PV System Testing @ UNLV

SNWA Pumping Station

Electricity production from renewables: concentrating Solar power

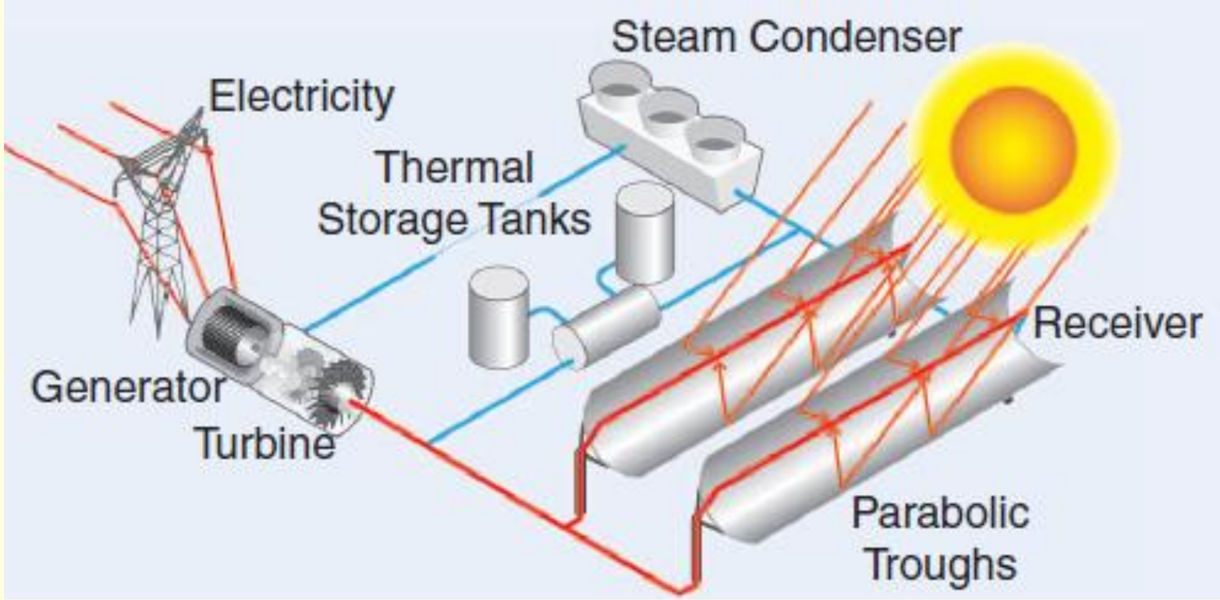


Concentrating Solar Power (CSP)

- CSP technologies use mirrors to reflect and concentrate sunlight onto receivers that collect the solar energy and convert it into heat.
- This thermal energy can then be used to produce electricity via a steam turbine or heat engine driving a generator.
- CSP systems are typically classified by how the various systems collect solar energy. The main systems are
  - The parabolic trough system
  - The linear Fresnel reflector system
  - The power tower system
  - The parabolic dish system

Parabolic trough systems

- Linear parabolic collectors capture the sun's energy with large mirrors that reflect and focus the sunlight onto a linear receiver tube.
- The receiver contains a fluid that is heated by the sunlight and then used to create steam that spins a turbine driving a generator to produce electricity.



Solar trough plant in Nevada: Nevada Solar 1 (65 MW)

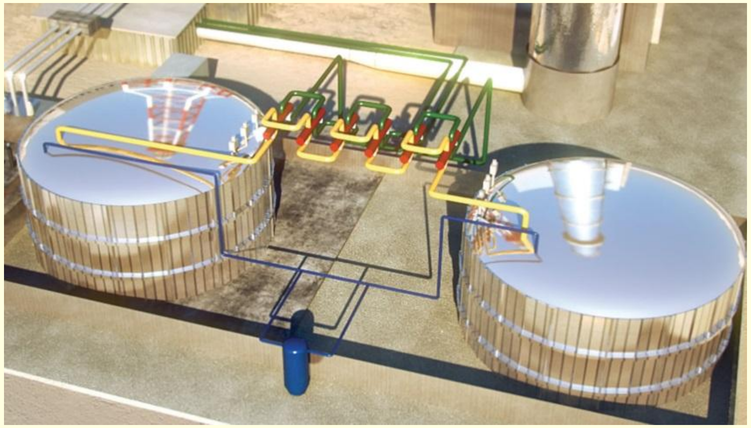
Linear Fresnel Reflector Systems

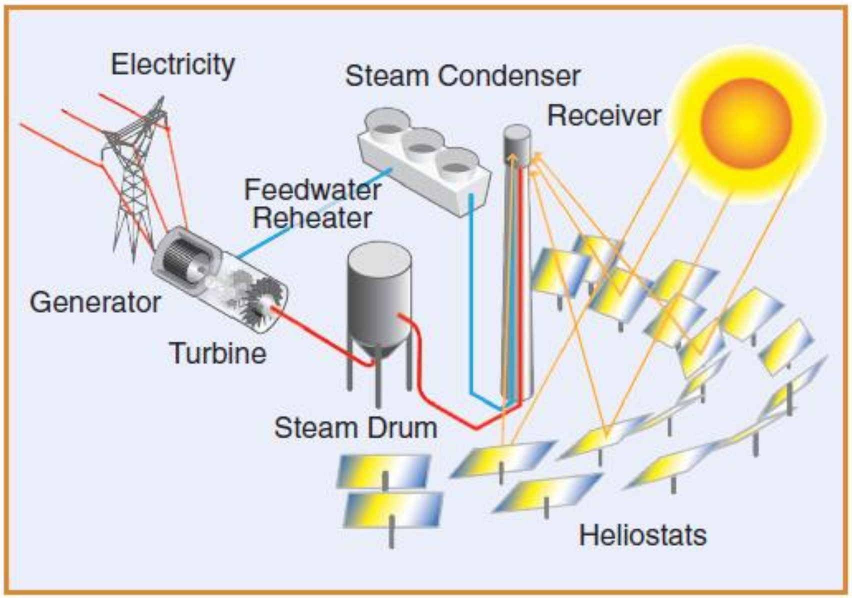
- Herein, the parabolic trough reflectors are replaced by independently controlled, flat glass mirrors mounted on a horizontal axis.
- Sunlight is reflected onto a fixed receiver mounted above the reflectors.
- The receiver can accommodate a number of high temperature fluids such as thermal oil, molten salt, or water.

Power Tower System

- Herein, numerous large, flat, sun-tracking mirrors (heliostats), focus sunlight onto a receiver at the top of a tower. A heat-transfer fluid heated in the receiver is used to generate steam, which in turn is used by turbine generator to produce electricity.
- Some power towers use water/steam as the heat transfer fluid. Other advanced designs are experimenting with molten nitrate salt because of its superior heat-transfer and energy-storage capabilities.

Thermal storage makes it possible to shift the time of power delivery.





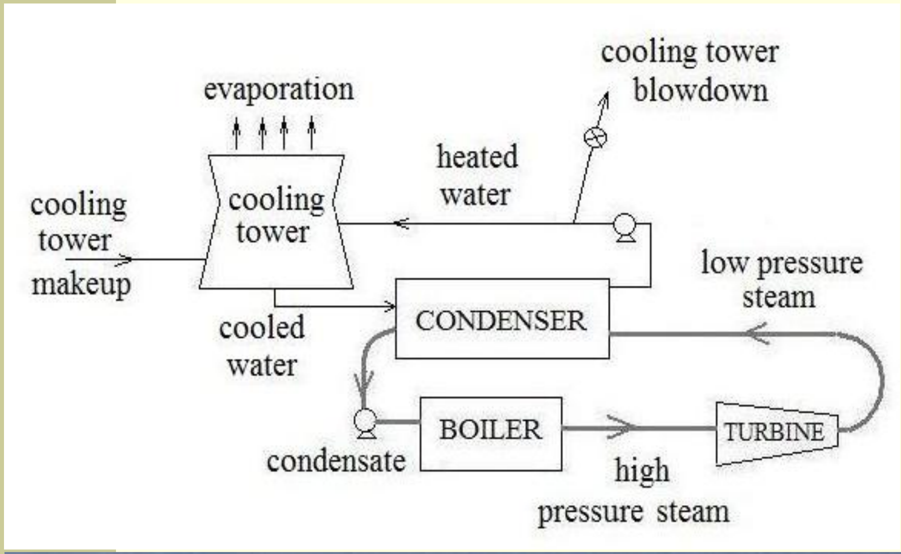
Power Tower Systems (Spain and California)

CA - NV Border @ I15

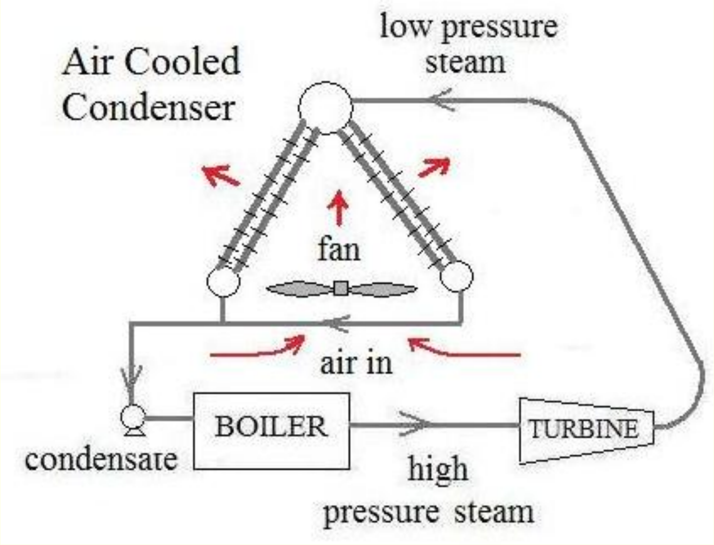
Southern Spain

Condenser Cooling for CSP systems:
(Water is a big challenge in arid deserts)

Wet Cooling

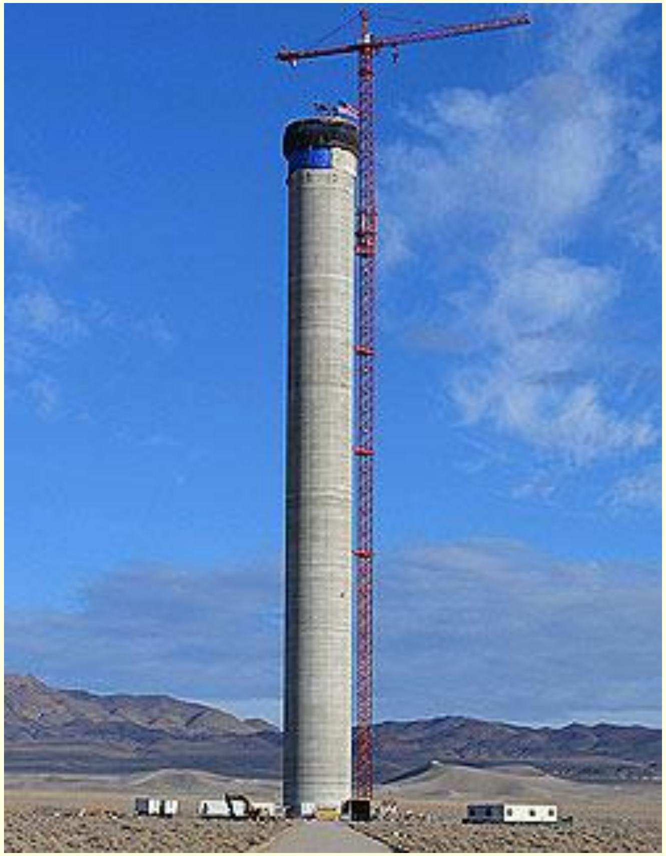


Dry Cooling



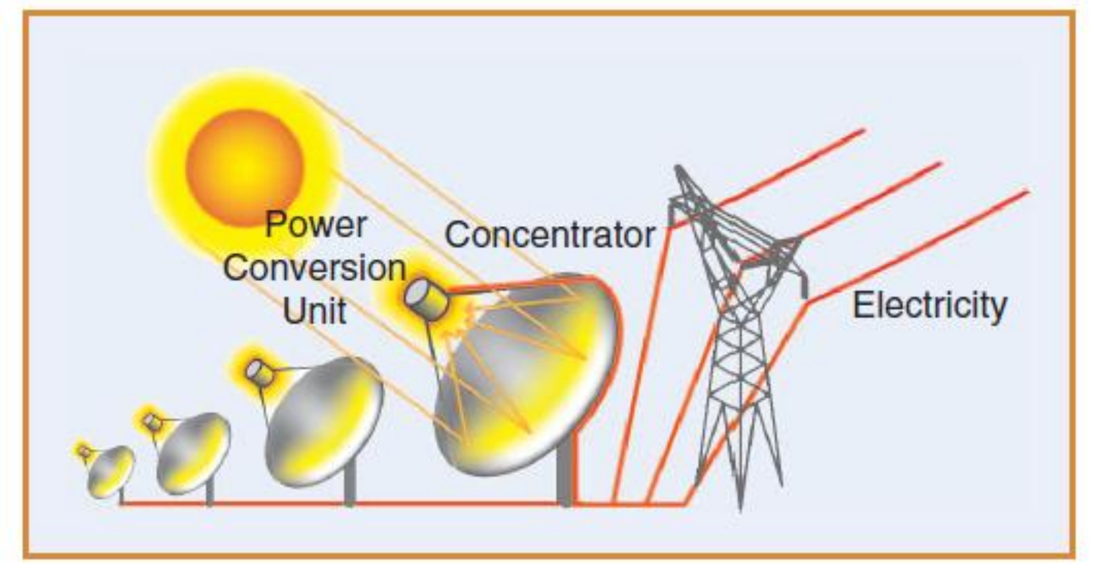
Power Tower CSP in Nevada: Crescent Dunes – 110 MW

- Location: near Tonopah, NV
- Completion date: 2014
- The system will use more than 17,000 heliostat mirrors to focus the sun's thermal energy to heat molten salt flowing from this 640-foot-tall solar power tower to underground storage tanks.



Dish/Engine CSP Systems

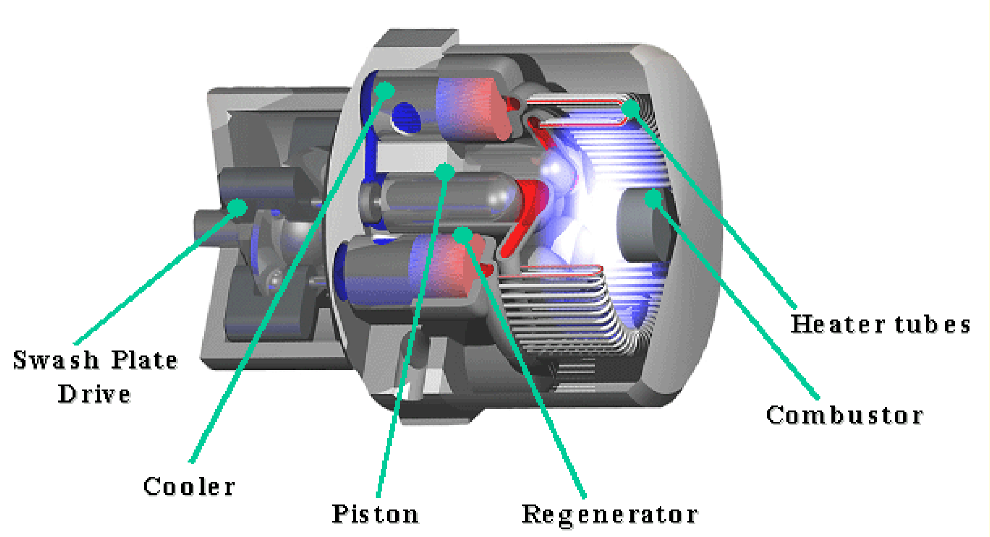
- A sun-tracking solar concentrator, or dish, reflects the beam of concentrated sunlight onto a thermal receiver that collects the solar heat.
- The power conversion unit includes the thermal receiver and the engine/generator. A thermal receiver can be a bank of tubes with a cooling fluid— usually hydrogen or helium—that typically is the heat transfer medium and also the working fluid for an engine.



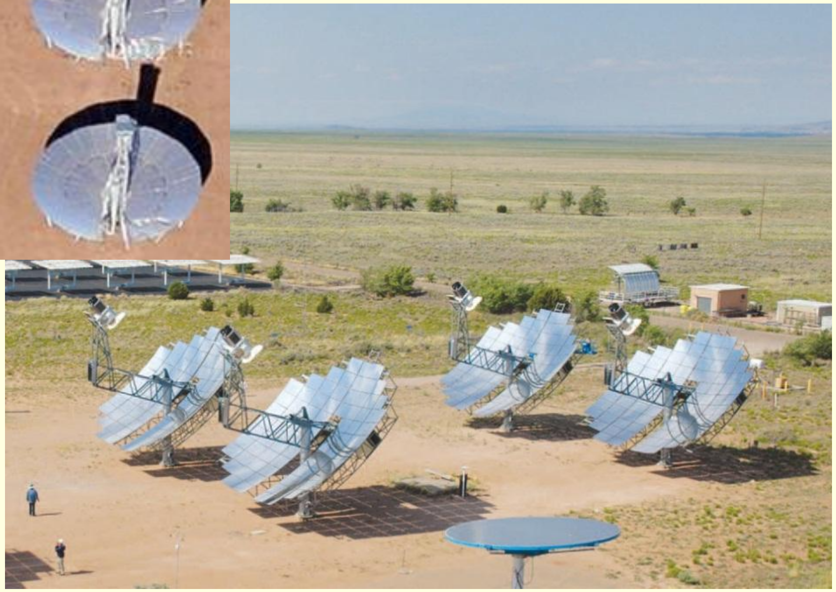
Dish CSP

- Currently, the most common type of heat engine used in dish/engine systems is the Stirling engine where the heated gas moves pistons and create mechanical power.
- Grid connection is through an induction machine.

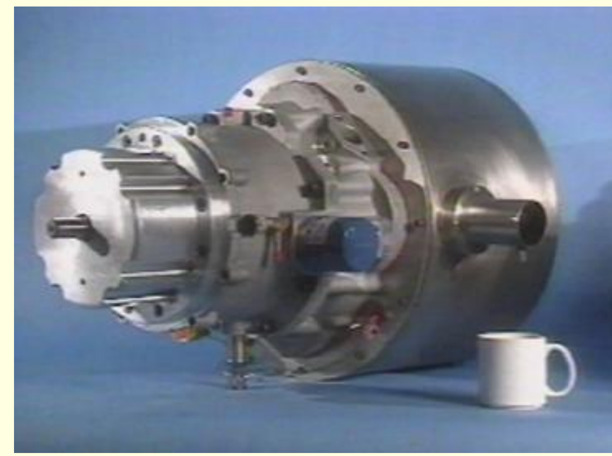
Heat engine concept

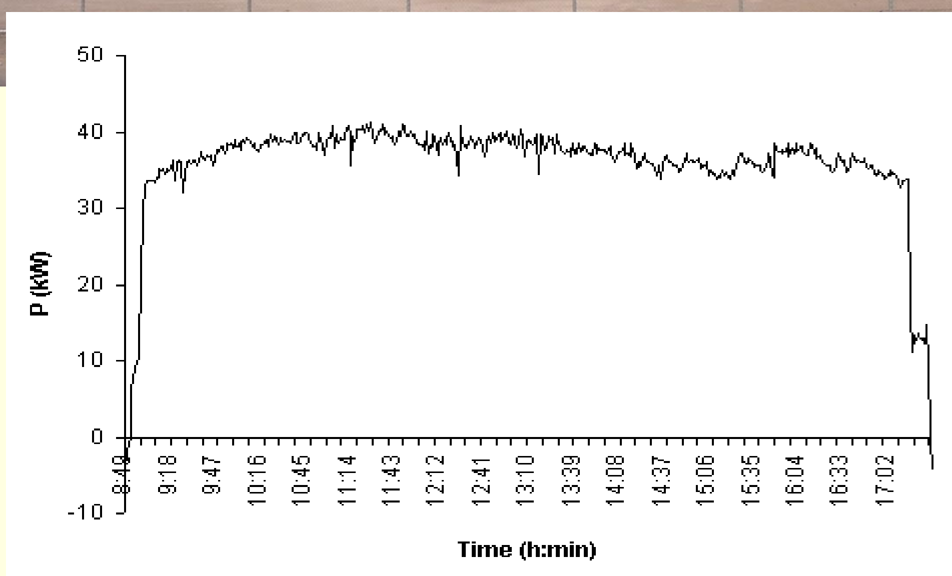


Dish/Engine CSP Systems – (in AZ and NM)



Dish-Engine CSP Testing @ UNLV





Efficiency ≈ 35%
(about half of the Carnot limit)

CSP Efficiency

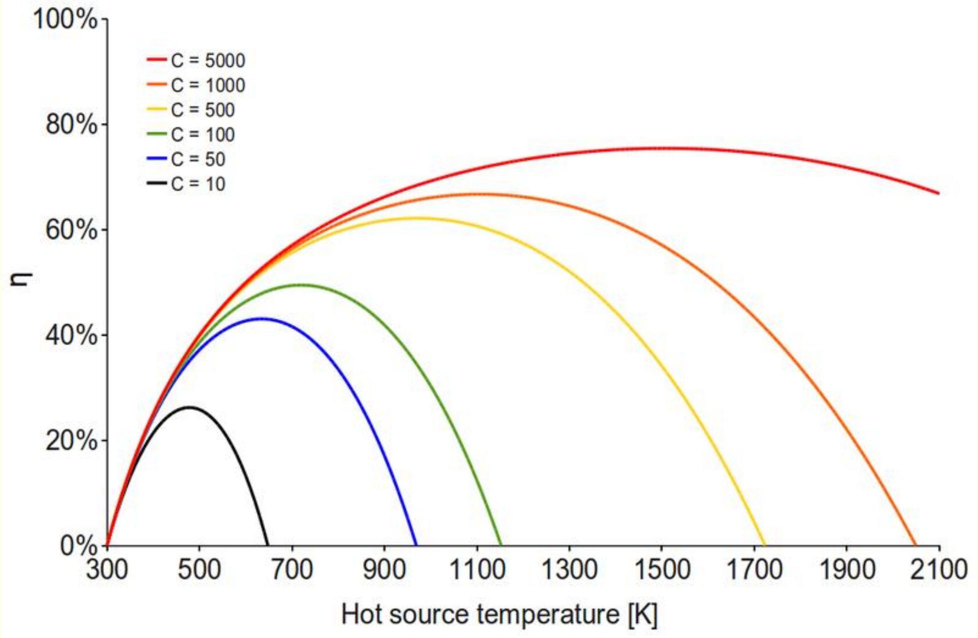
$$\eta = \eta_{\text{Receiver}} \cdot \eta_{\text{Carnot}}$$

$$\eta_{\text{Carnot}} = 1 - \frac{T^0}{T_H}$$

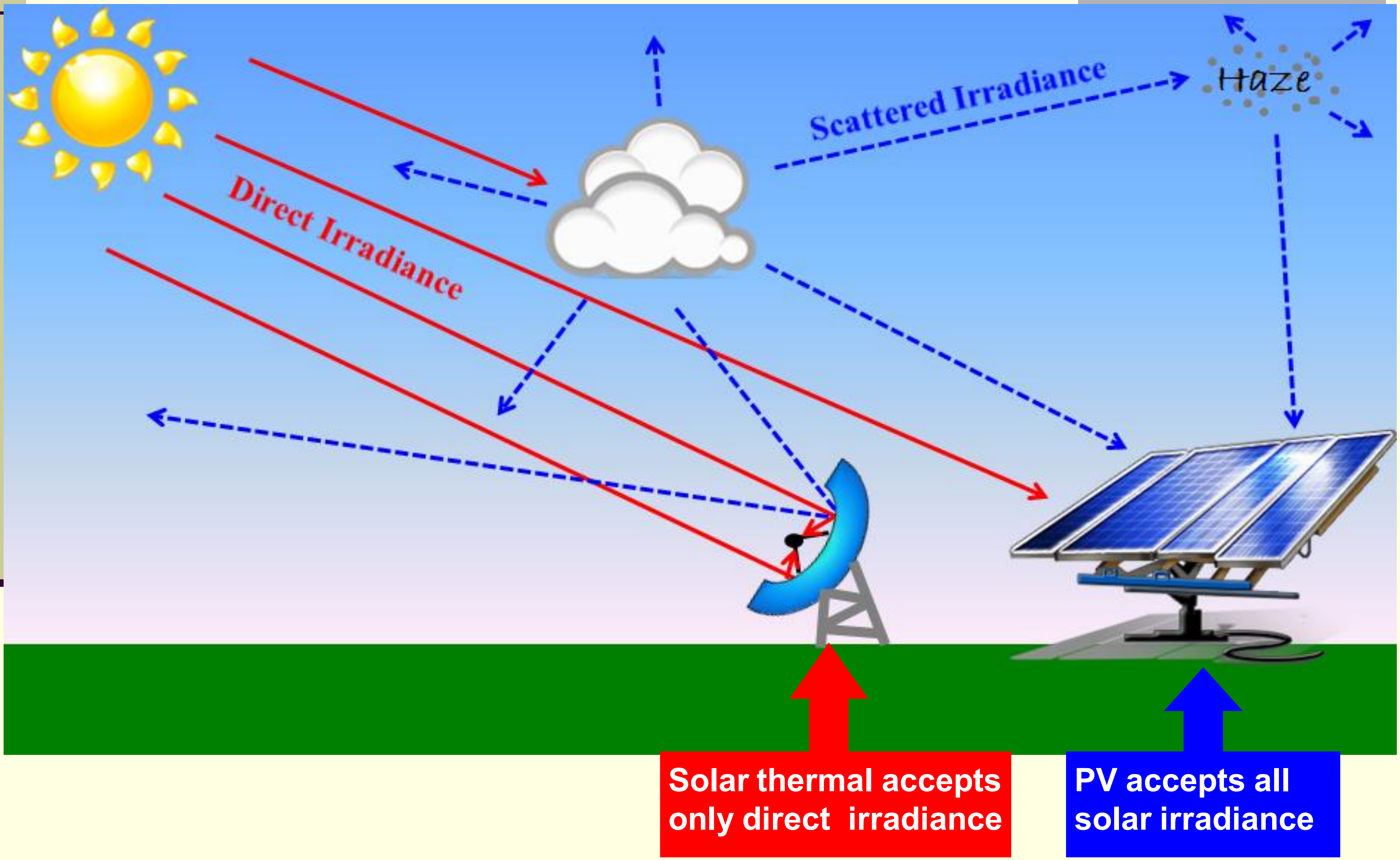
$$\eta_{\text{Receiver}} = \frac{Q_{\text{absorbed}} - Q_{\text{lost}}}{Q_{\text{solar}}}$$

$$\eta = \left(1 - \frac{\sigma T_H^4}{IC}\right) \cdot \left(1 - \frac{T^0}{T_H}\right)$$

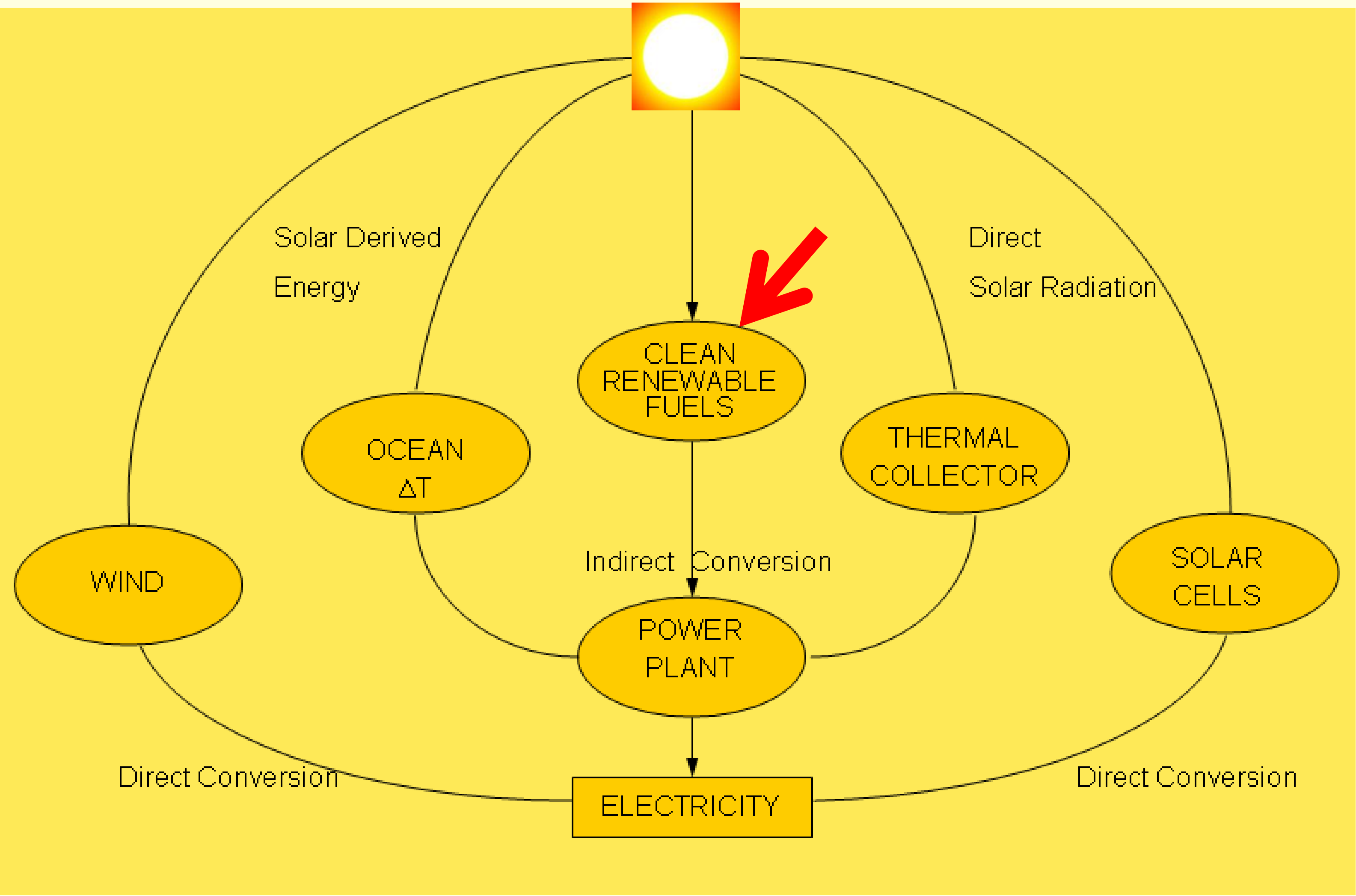
- T_H and T° : heat source at temperature and a heat sink temperatures (in deg. Kelvin)
- Q_{solar}, $Q_{absorbed}$, Q_{lost} : incoming solar flux and the fluxes absorbed and lost by the solar receiver.
- I, C, σ: solar flux, concentration factor, absorptivity (<1).



Unlike PV, concentrated solar thermal systems depend only on direct irradiance!

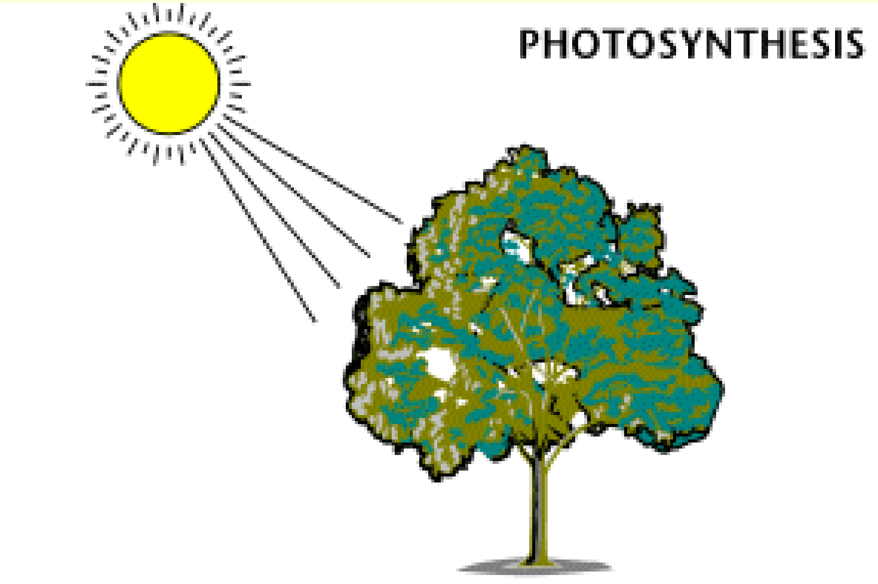


Electricity production from renewables: Biomass



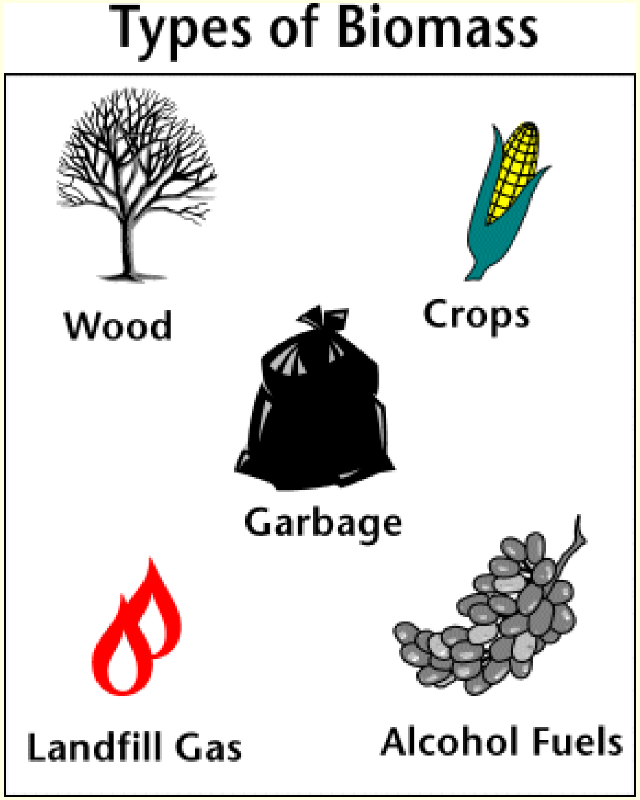
Biomass

- Biomass is organic material made from plants and animals (micro-organisms).
- Biomass contains stored energy from the sun: Plants absorb the sun's energy through photosynthesis. The chemical energy in plants (in the form of glucose or sugar) gets passed on to animals and people that eat them.



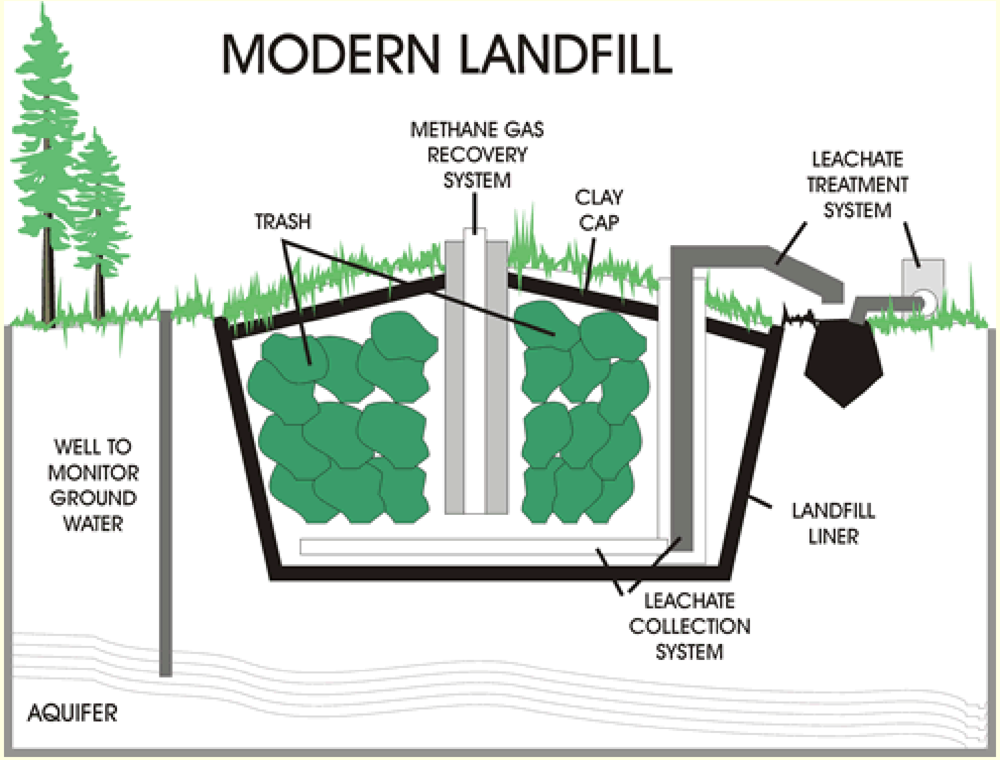
Biomass Energy

- The most common form of biomass is wood. Wood was the main source of energy until the mid-1800s.
- Biomass can be used to make an energy-rich gas or biogas - like natural gas.
- Biomass can also be turned into a fuel like gasoline - corn and wheat can be made into ethanol.
- Biomass can also be used to make electricity. Many towns, instead of putting the garbage in landfills, they burn it to make electricity.
- Landfills can be a source of energy. Anaerobic bacteria that live in landfills decompose organic waste to produce methane gas.



Biomass Energy from landfills

- As of 2011, over 550 landfills have operating gas to energy projects in the United States.

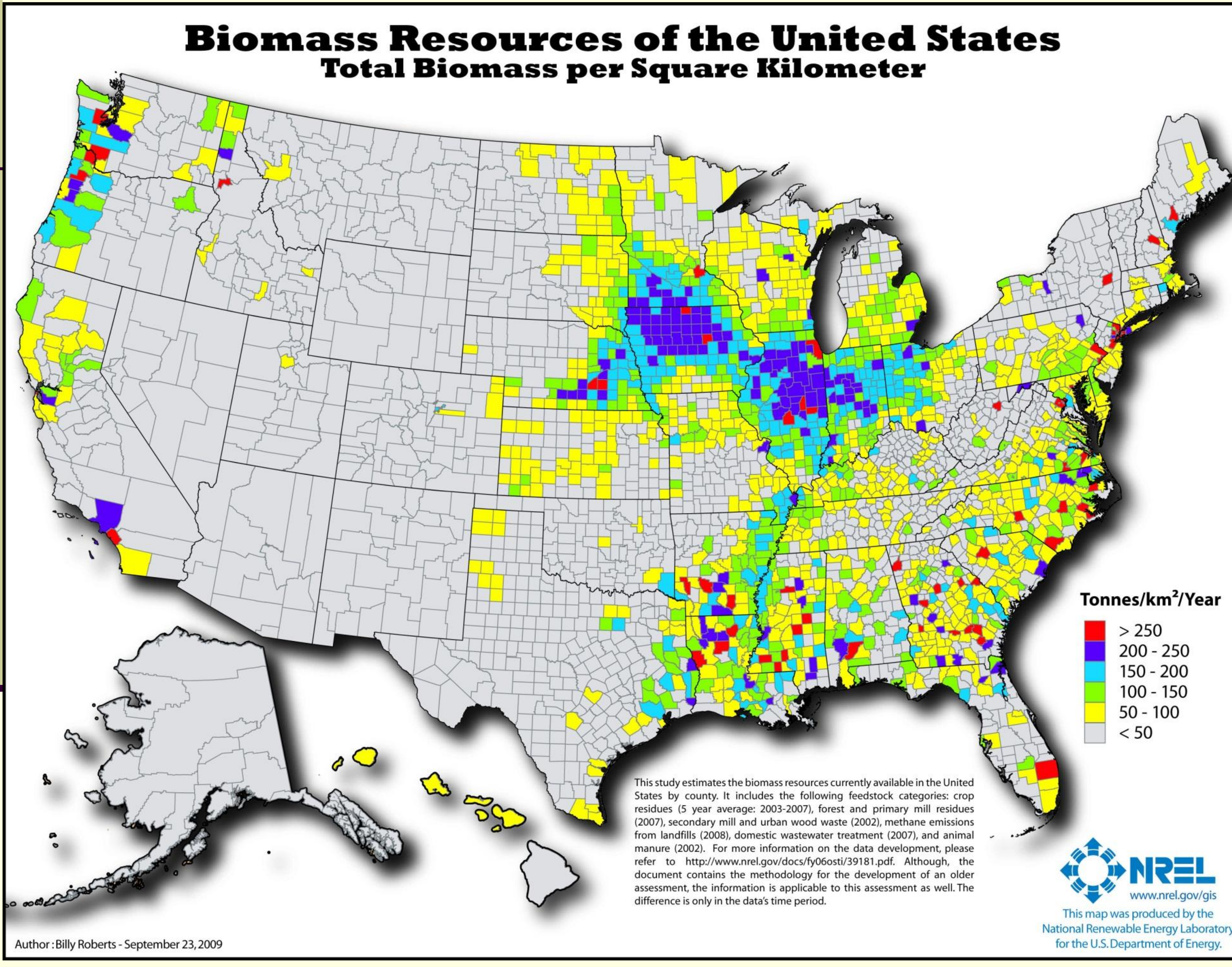


Source: http://www.eia.gov/biogas/

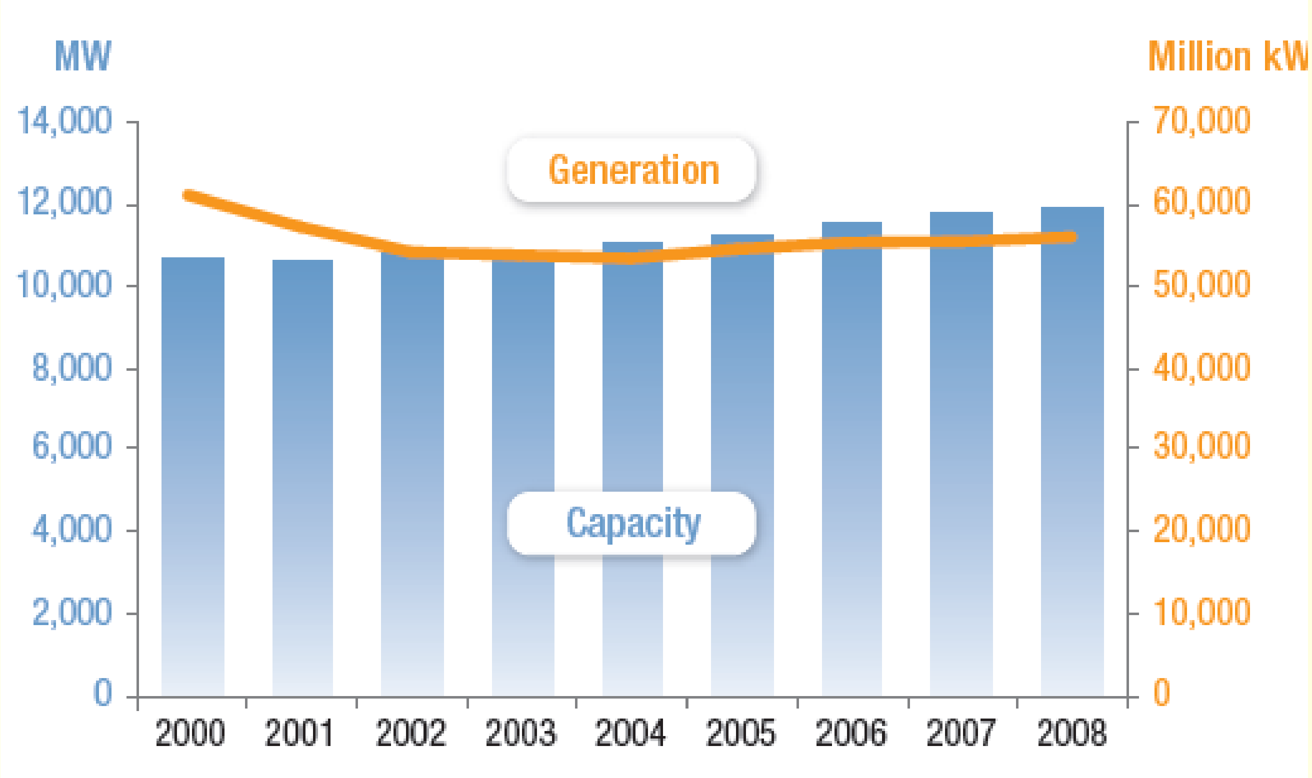
Biomass in Nevada:
CC Landfill Energy LLC :12.0 MW

Biomass energy from animal waste

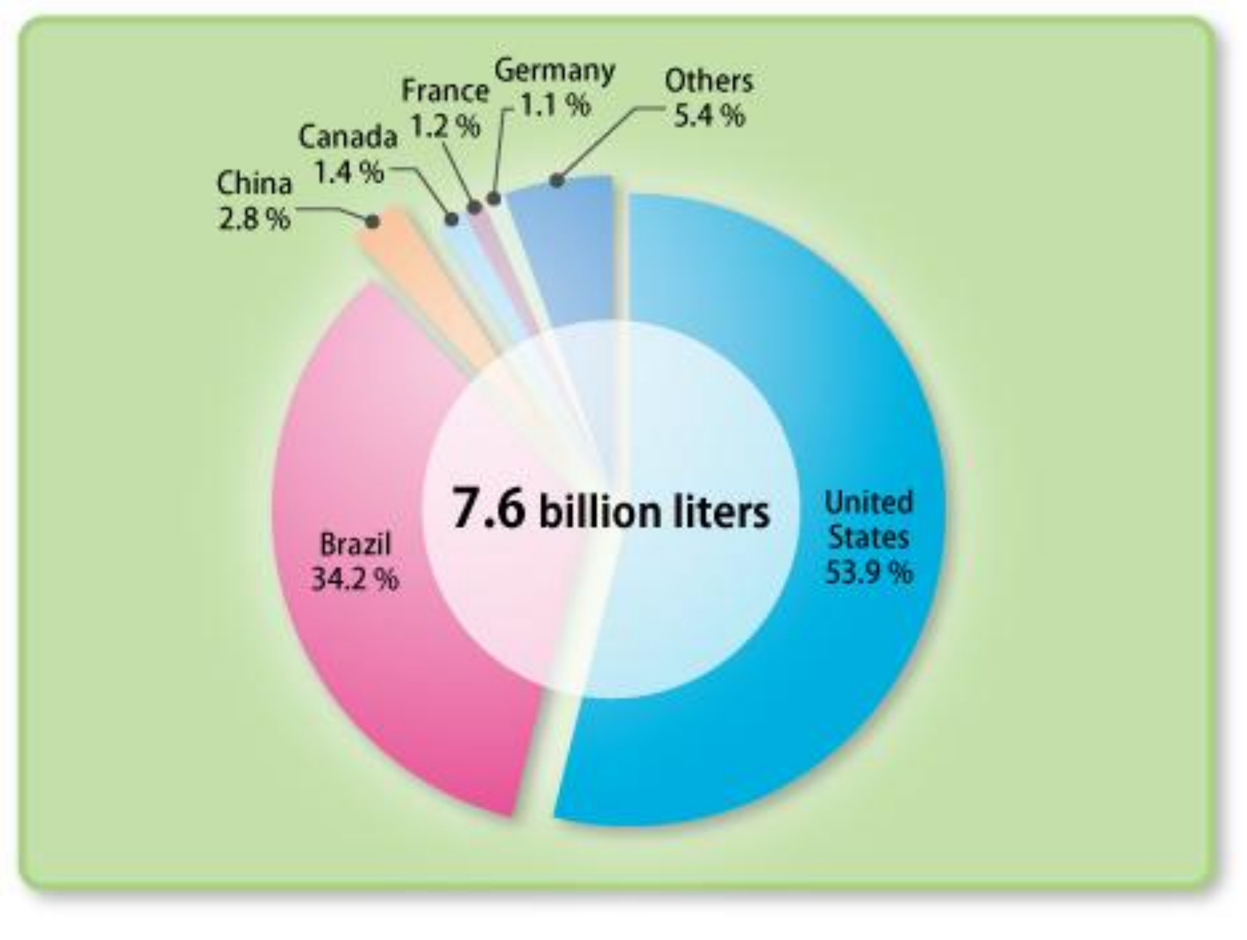
Some farmers produce biogas in large tanks called "digesters" where they put manure and bedding material from their barns. Some cover their manure ponds to capture biogas. Biogas digesters and manure ponds contain the same anaerobic bacteria in landfills.


Biomass Resources of the United States
Total Biomass per Square Kilometer
Tonnes/km²/Year
> 250
200 - 250
150 - 200
100 - 150
50 - 100
< 50
This study estimates the biomass resources currently available in the United States by county. It includes the following feedstock categories: crop residues (5 year average: 2003-2007), forest and primary mill residues (2007), secondary mill and urban wood waste (2002), methane emissions from landfills (2008), domestic wastewater treatment (2007), and animal manure (2002). For more information on the data development, please refer to http://www.nrel.gov/docs/fy06osti/39181.pdf. Although, the document contains the methodology for the development of an older assessment, the information is applicable to this assessment as well. The difference is only in the data's time period.
NREL
www.nrel.gov/gis
This map was produced by the National Renewable Energy Laboratory for the U.S. Department of Energy.
Author: Billy Roberts - September 23, 2009

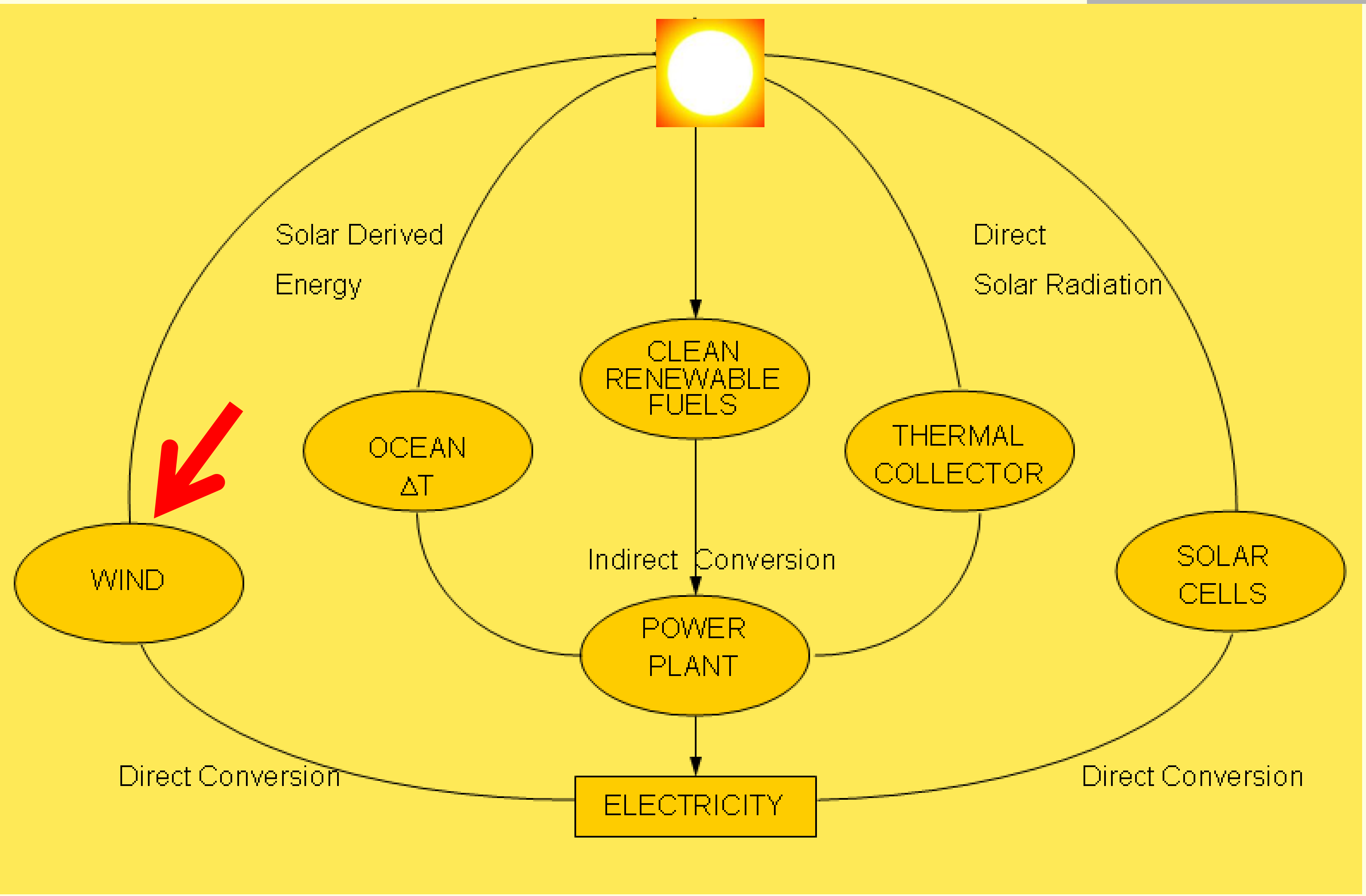
US Bio-Power capacity



Biomass – bioethanol production (2011)



Electricity production from renewables: Wind

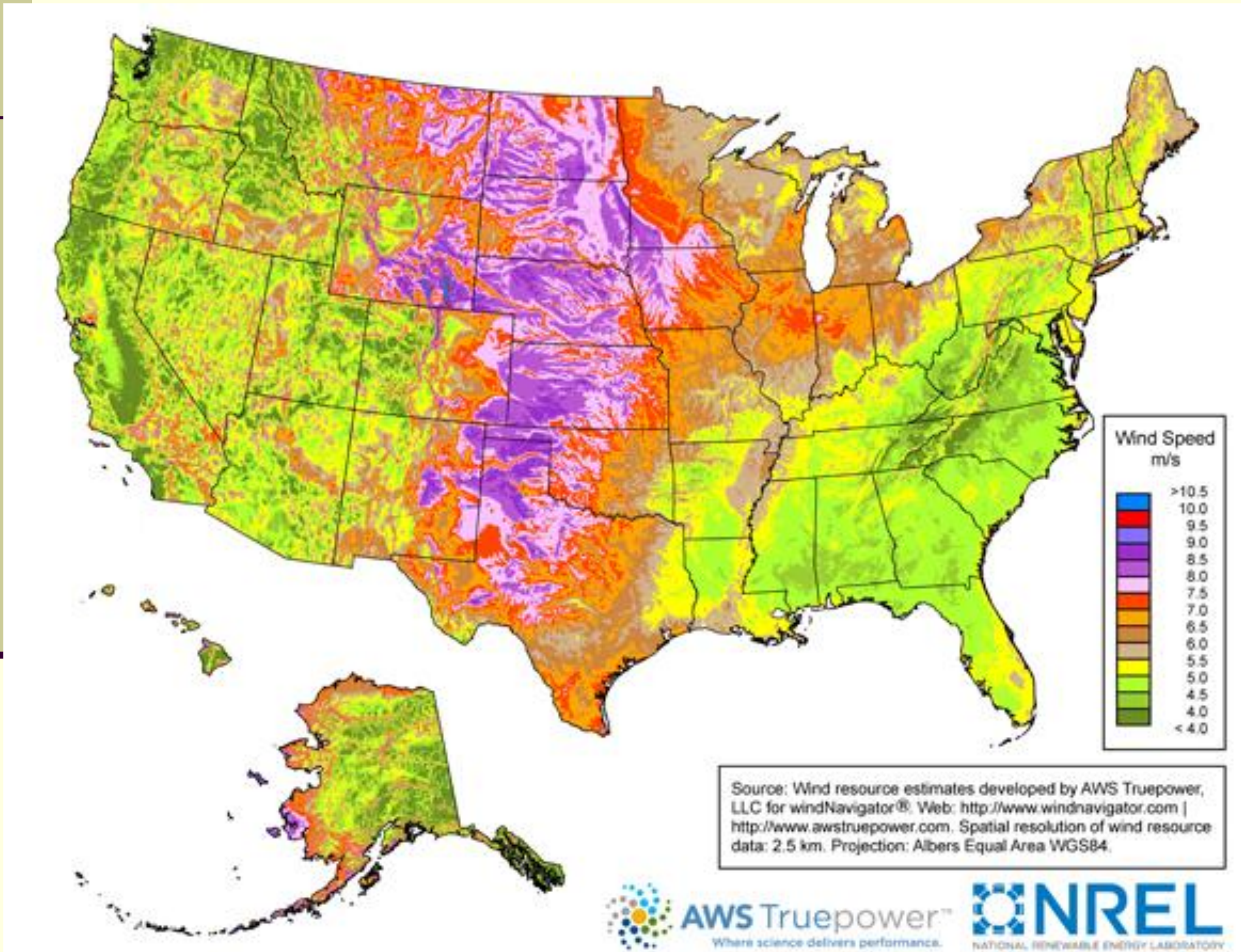


Wind Power … Inland and Offshore

Installed Wind Capacity by Country (MW)

#	Nation	2005	2006	2007	2008	2009	2010	2011
-	European Union	40,722	48,122	56,614	65,255	74,919	84,278	93,957
1	China	1,266	2,599	5,912	12,210	25,104	44,733	62,733
2	United States	9,149	11,603	16,819	25,170	35,159	40,200	46,919
3	Germany	18,428	20,622	22,247	23,903	25,777	27,214	29,060
4	Spain	10,028	11,630	15,145	16,740	19,149	20,676	21,674
5	India	4,430	6,270	7,850	9,587	10,925	13,064	16,084
6	France	779	1,589	2,477	3,426	4,410	5,660	6,800
7	Italy	1,718	2,123	2,726	3,537	4,850	5,797	6,747
8	United Kingdom	1,353	1,963	2,389	3,288	4,070	5,203	6,540
9	Canada	683	1,460	1,846	2,369	3,319	4,008	5,265
10	Portugal	1,022	1,716	2,130	2,862	3,535	3,702	4,083
11	Denmark	3,132	3,140	3,129	3,164	3,465	3,752	3,871
12	Sweden	509	571	831	1,067	1,560	2,163	2,970

US Wind Resource Map



Wind turbines

- Horizontal axis wind turbines (HAWT) are the most popular - compared to vertical axis wind turbines (VAWT).
- 3 blades used to minimize power pulsations (if < 3) and aerodynamic interference (if > 3).
- The aerodynamic blades produce a lift force along the blade which produces a mechanical torque on the turbine shaft.



Wind and Turbine Power

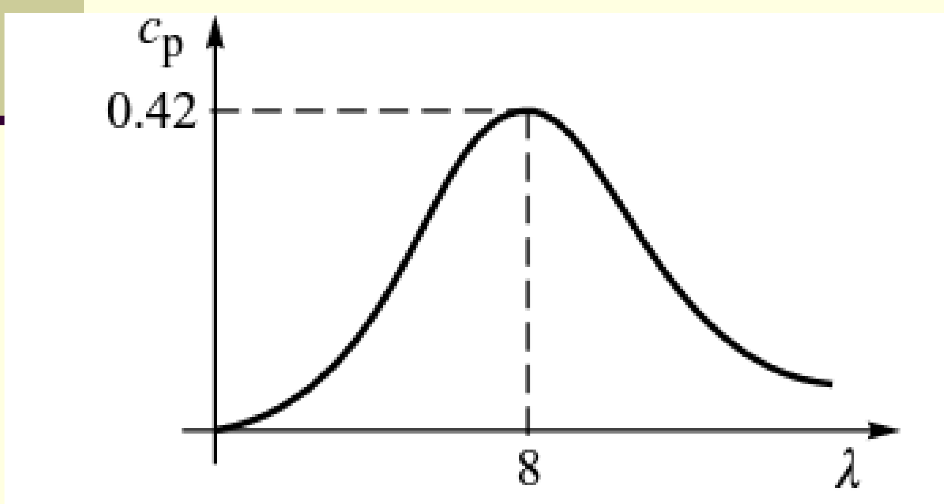
- Power of the wind: $\mathbf{P_w = (1/2)\rho A v_w^3}$
- Where ρ is the air density, A is turbine sweep area, and v_w is the wind speed.
- Power extracted by the turbine: $\mathbf{P_t = c_p P_w}$

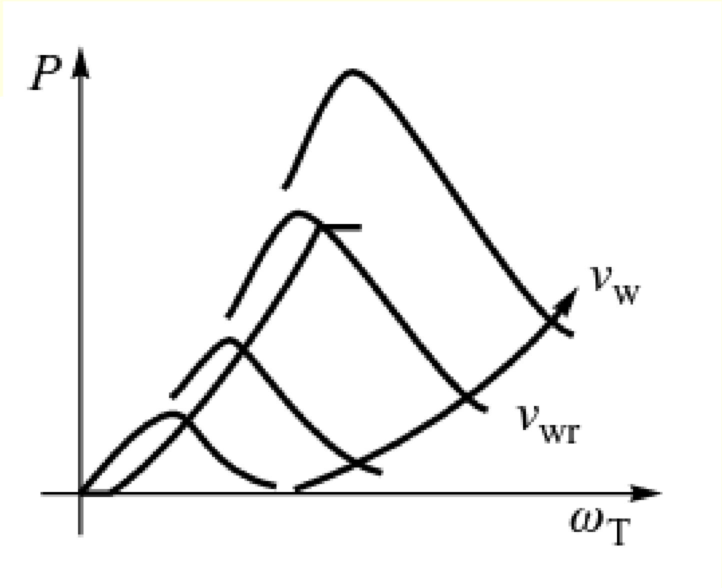
  where c_p is the turbine performance coefficient.
- The theoretical maximum value of c_p (derived from the conservation of mass and energy) is 16/27 ≈ 60%.
- In practice c_p is less than the above value and its varies with the tip speed ratio: $\mathbf{\lambda = \omega r/v_w}$

  where ω is the rotor speed r is the rotor radius and v_w is the wind speed.

Turbine Power

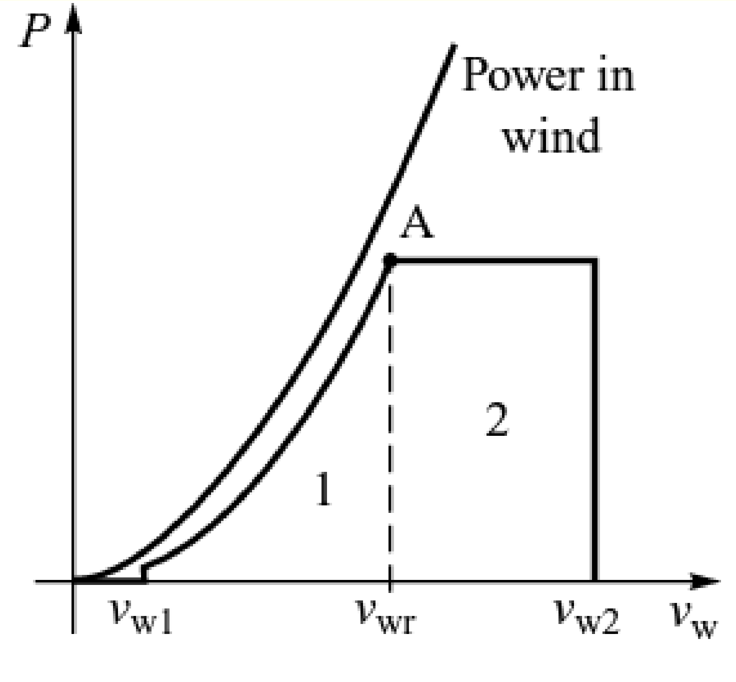
- A typical c_p - λ curve is shown below and is unique to a particular turbine design. Modern wind turbine design can reach 70-80% of the theoretical limit.
- To extract maximum power, the turbine must be operated at the peak of the curve (*peak power tracking*).
- For a given wind speed v_w and the c_p - λ characteristics, the turbine power can be calculated as a function of shaft speed.





Turbine Power

- For a given turbine c_p, the turbine power can be graphed as a function of the wind speed as shown below.
- The figure shows the cut-in speed (3-4 m/s), rated speed (12.5 m/s), and shut down speed (around 25 m/s).
- Turbines are typically designed to withstand wind speeds of up to 50 m/s (180 km/hr)



Average Power in the Wind

- The average power in the wind is proportional to the average of the cube of the wind velocity, not the cube of the average wind speed.

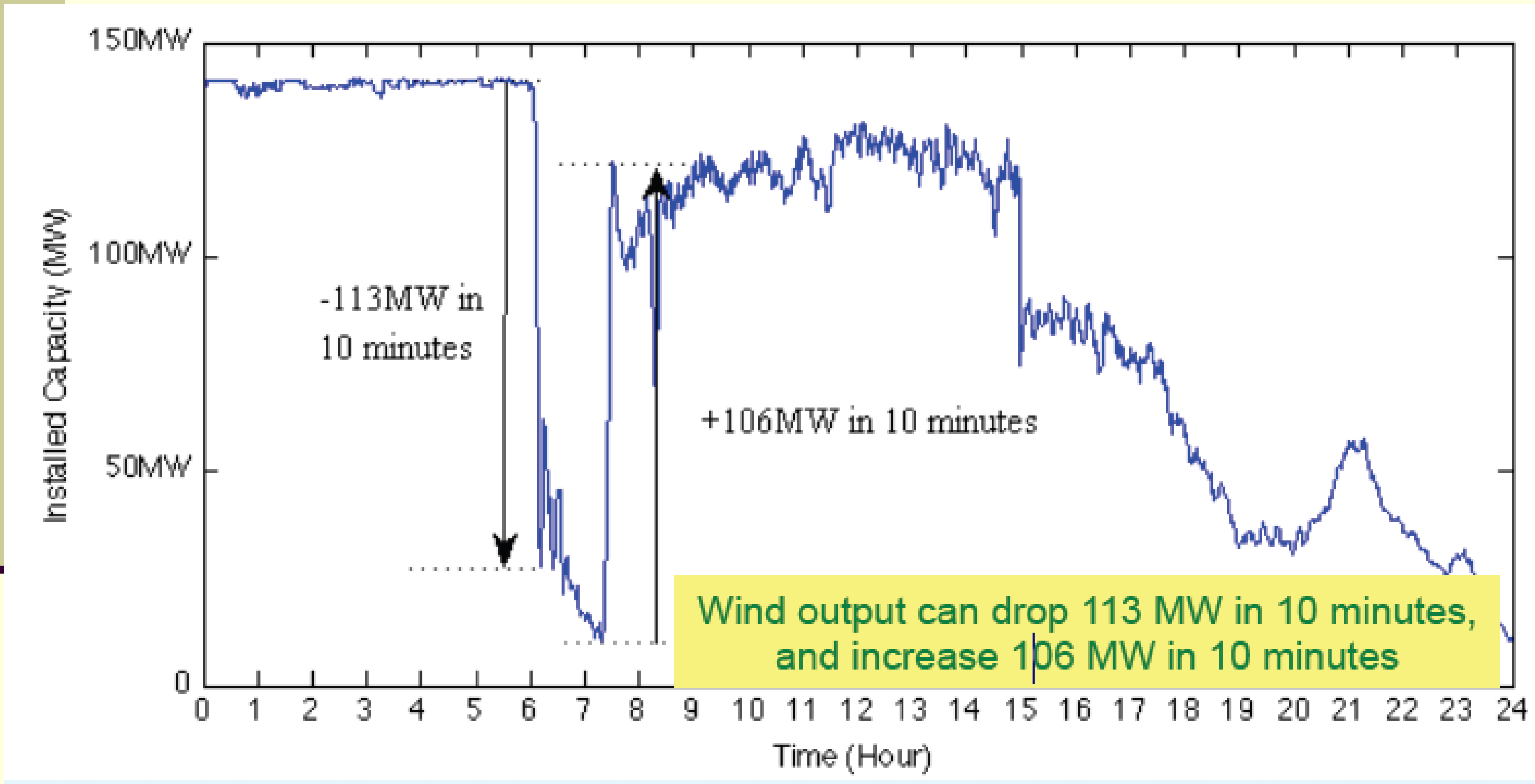
$$P_{avg} = (\frac{1}{2}\rho A v^3)_{avg} = \frac{1}{2}\rho A (v^3)_{avg} \neq \frac{1}{2}\rho A (v_{avg})^3$$

- Example: Calculate the cube of the average value and the average of the cube of the wind if

$$v(t) = V_M \,|\sin t\,|$$

Ans: $(v_{avg})^3 = \frac{8}{\pi^3}V_M^3 \approx 0.26V_M^3, \qquad (v^3)_{avg} = \frac{4}{3\pi}V_M^3 \approx 0.42V_M^3$

Wind intermittency: Important issue



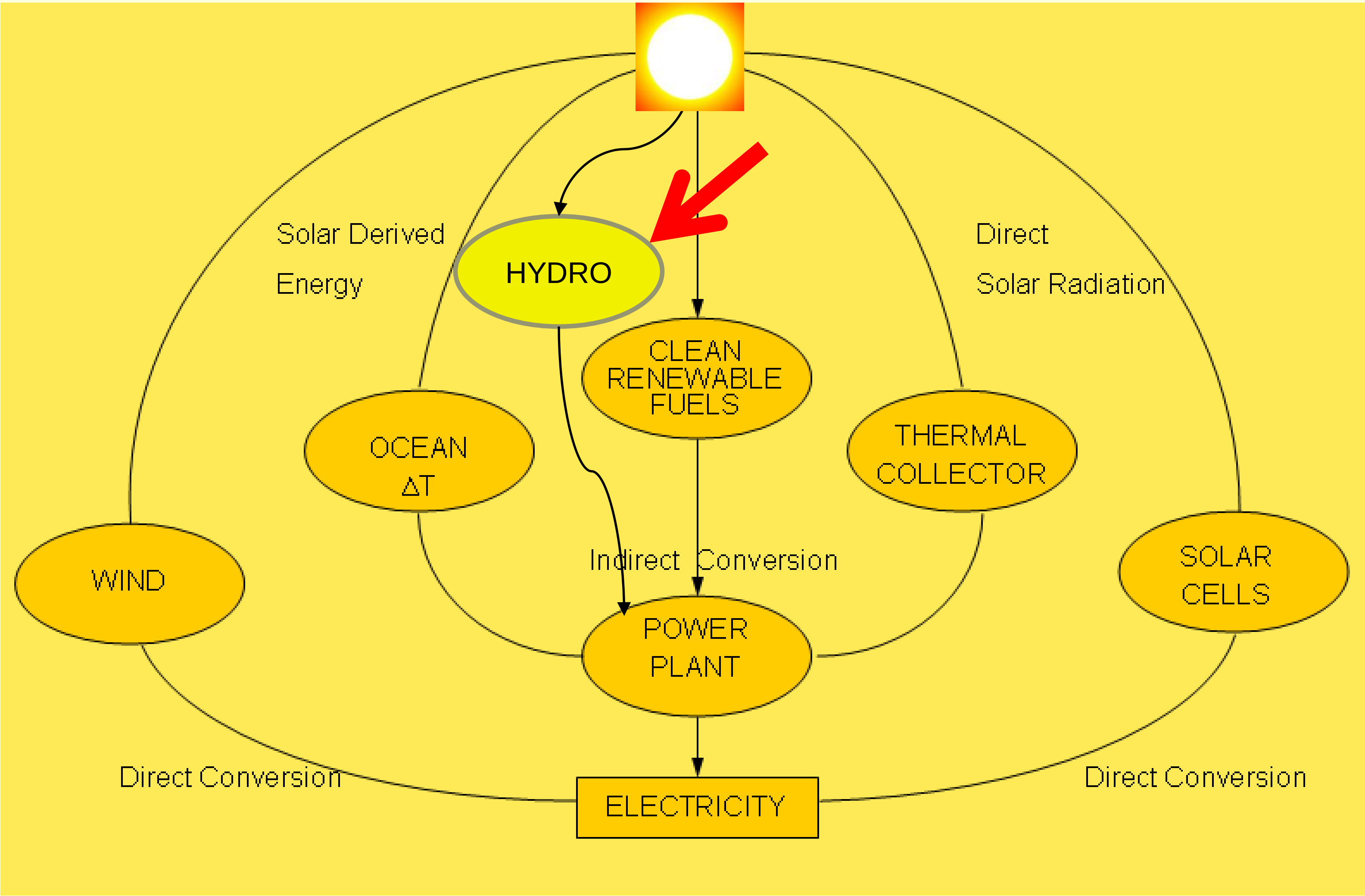
Source: NREL

Largest wind turbine generator to date:

- Manufacturer: Enercon
- Rated power: 6 MW,
- Rotor diameter: 126 m,
- Total height; 198 m.

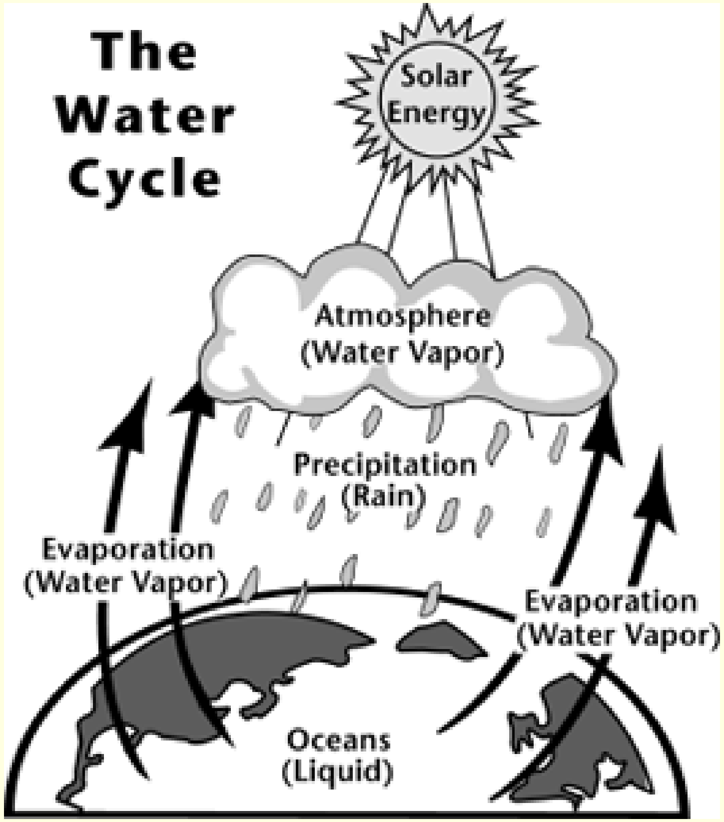
Wind Power in Nevada:
Spring Valley Wind (Pine County): 152 MW

Electricity production from renewables: hydro



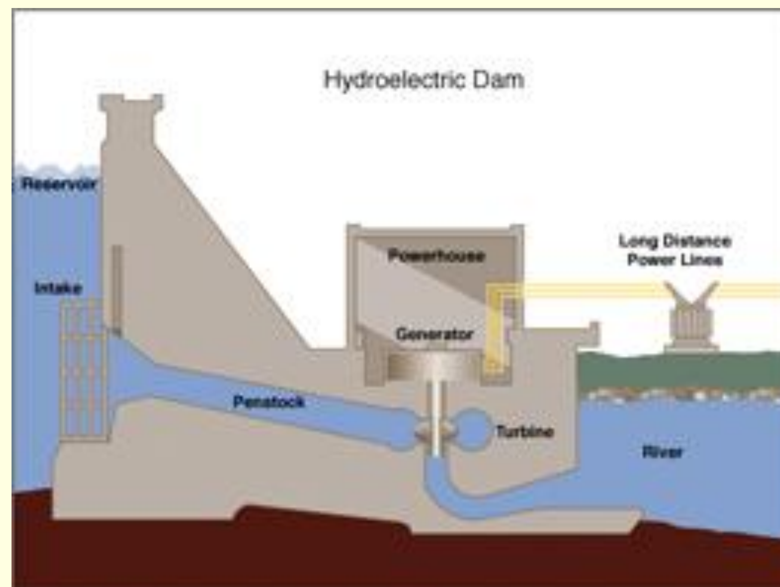
Hydropower

- Hydropower relies on the water cycle. Herein:
  - Solar energy heats water on the surface, causing it to evaporate.
  - This water vapor condenses into clouds and falls back onto the surface as precipitation (rain, snow, etc.).
  - The water flows through rivers back into the oceans, where it can evaporate and begin the cycle over again



Hydropower

- The amount of available energy in moving water is determined by its flow rate or fall.
  - Swiftly flowing water in a big river carries a great deal of energy in its flow.
  - Water descending rapidly from a very high point also has lots of energy in its flow.
- In either instance, the water flows through a pipe, or *penstock*, pushes against and turns blades in a turbine to spin a generator to produce electricity.

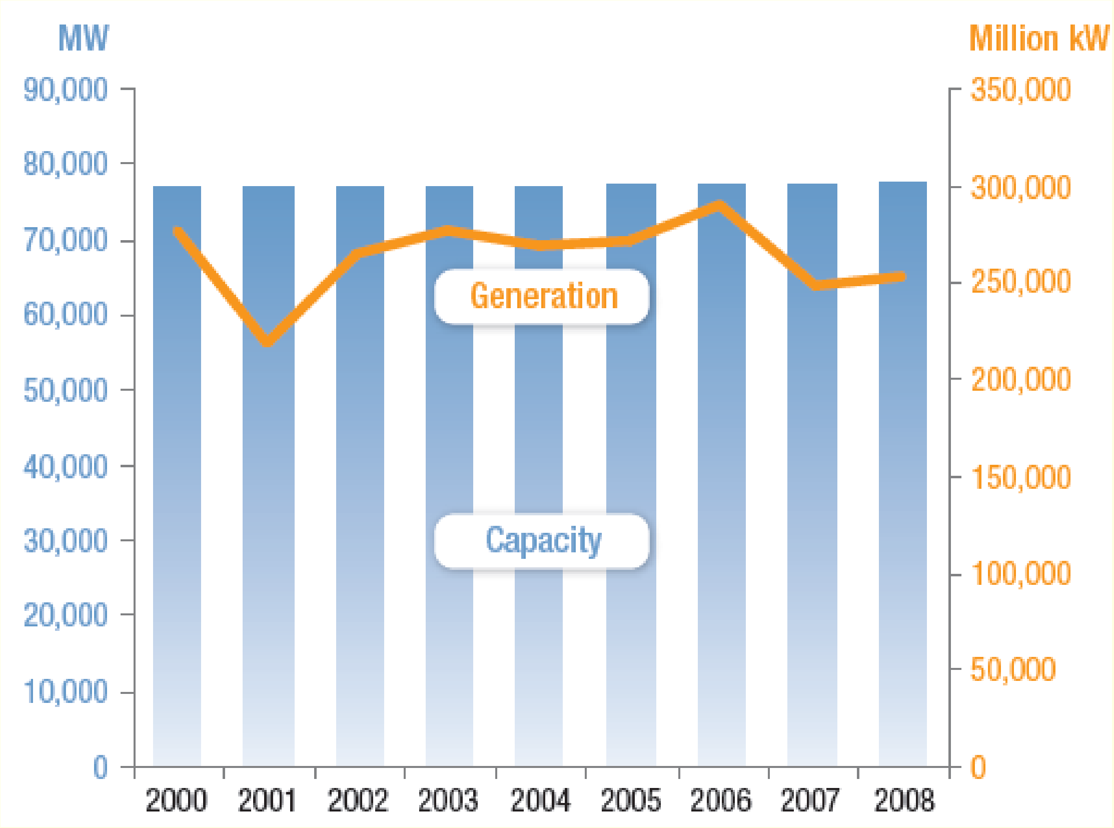


Hydropower in the USA

- Hydropower is the renewable energy source that produces the most electricity in the United States. It accounted for 6% of total U.S. electricity generation and 63% of generation from renewables in 2011.
- Most hydropower is produced at large facilities built by the federal government.
  - Only a small percentage of all dams in the United States produce electricity.
  - Most dams were constructed solely to provide irrigation and flood control.

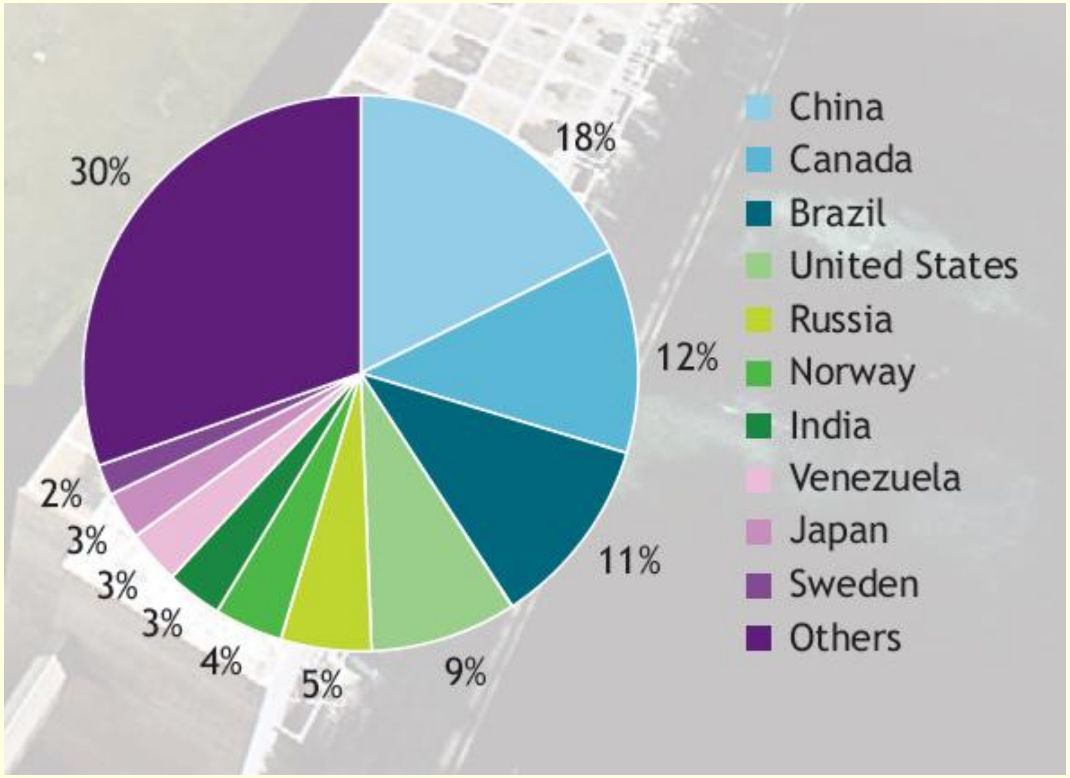
US Hydropower Capacity

- 345 large plants (>30MW) with a total rating of 67 GW
- Nearly 900 small plants (1-30 MW) with total rating of 10 GW



Hydropower in the world

- As of 2010, 16.3% of global electricity production is generated from hydropower.
- The Three Gorges Dam in China, has the world's largest generating capacity (22.5 GW), followed by the Itapúa Dam in Brazil (14 GW)



Power of a hydro power plant

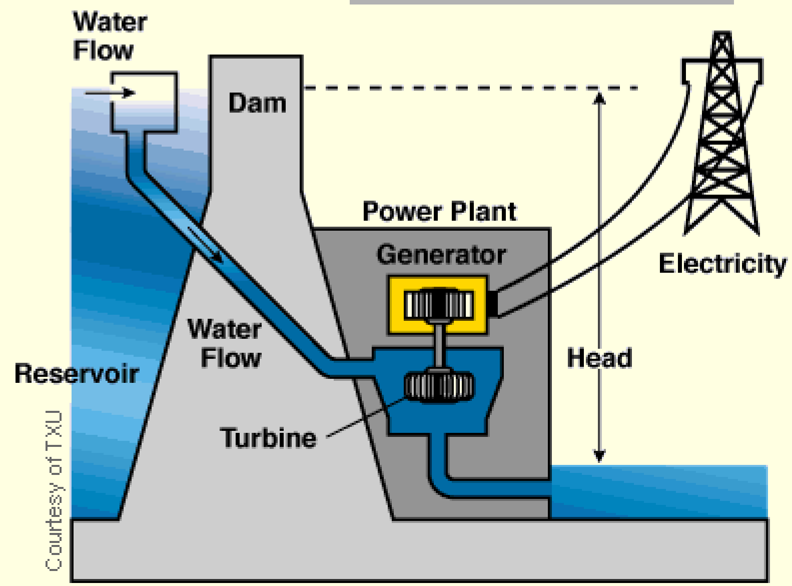
- Ideal case

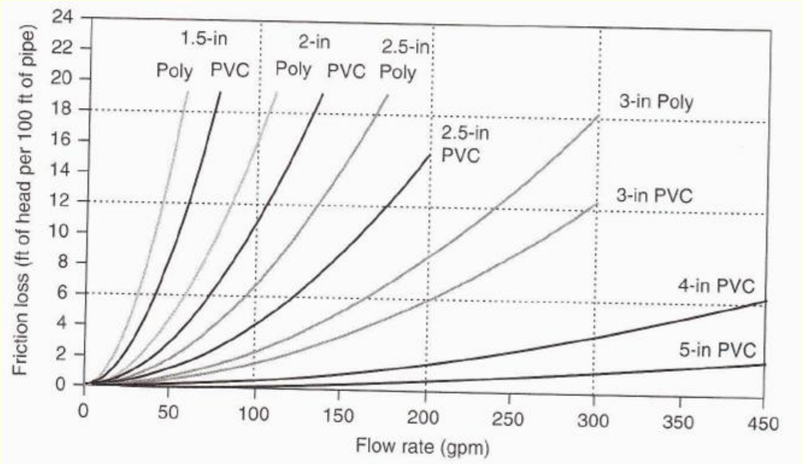
$$P = 9.81QH_G$$

- When friction losses in the penstock and in the turbine-generator.

$$P = 9.81\eta QH_N$$

  - P: Power (kW)
  - Q: flow rate (m^3/s)
  - H_G: gross head (m)
  - η: turbine-generator efficiency
  - H_N: net head (m) (= gross head – head loss). Head loss depends on the type of material, diameter, flow rate, and length.



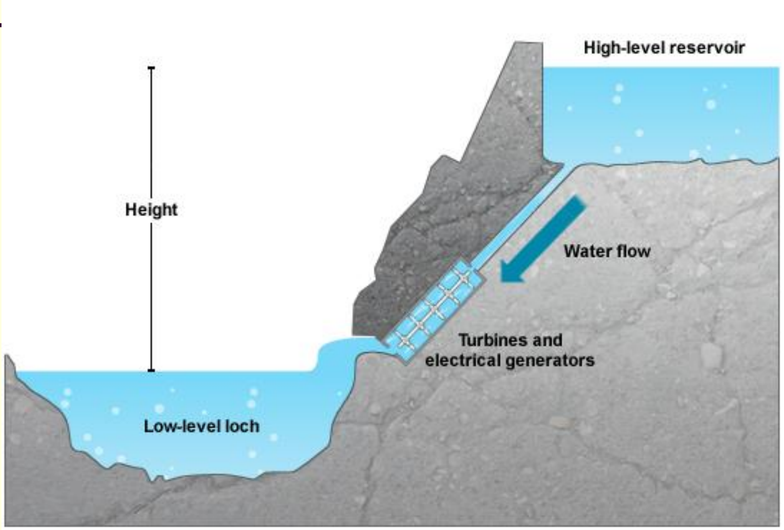


Pumped-Storage Hydro

- Used in bulk power storage applications where water is pumped up at night and released during the day.
- Energy available in upper reservoir:

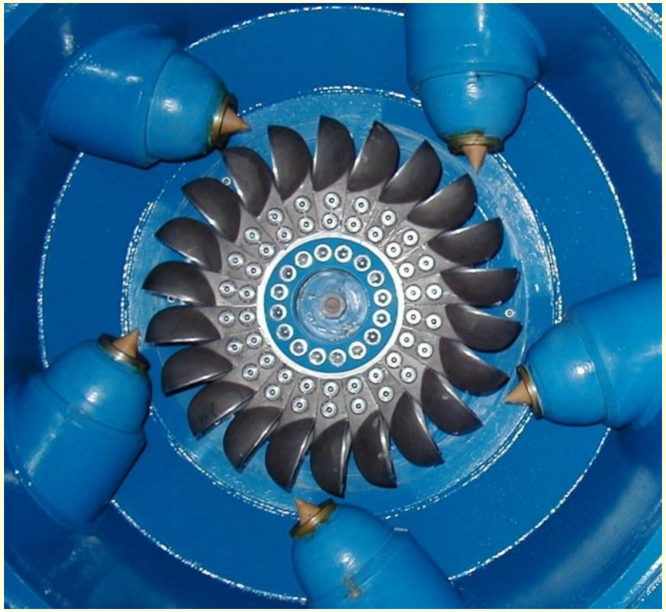
$$E = \frac{\rho A g H (\Delta h)}{3.6\ 10^6}$$

  - E: Energy (kWh)
  - ρ: water density (1000 kg/m^3)
  - A: surface area of upper reservoir (m^2)
  - Δh: Allowable change in surface level (m)
  - g: gravitational acceleration (9.81 m/s^2)
  - H: average height between the two reservoirs (m).



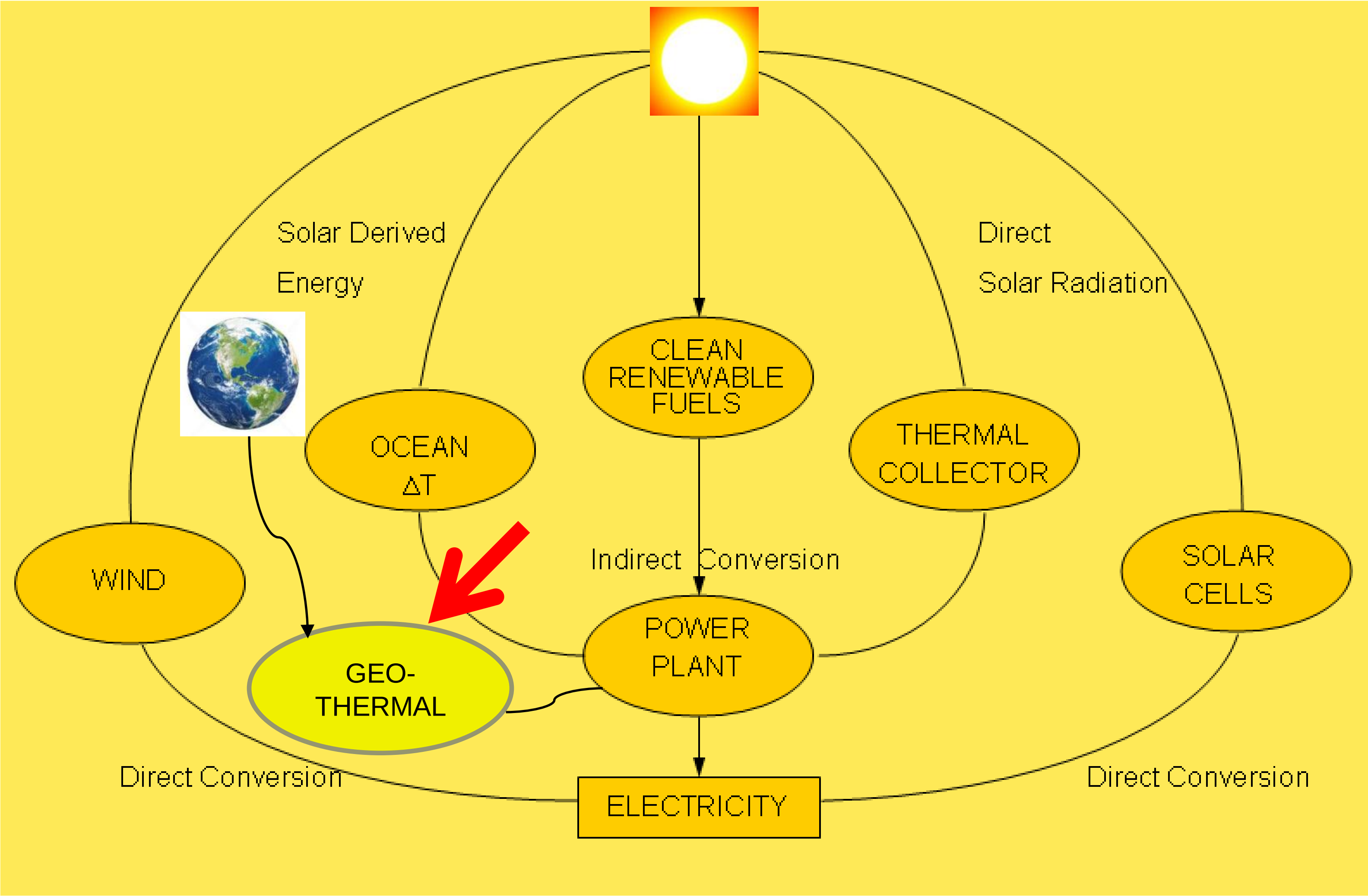
Small Hydro Power Plants in Northern Nevada:

- **Fleish:** 2.3 MW
- **Hooper:** 0.8 MW
- **Truckee Irrigation District:** 4.0 MW
- **Verdi:** 2.2 MW
- **Washoe:** 2.2 MW



Pelton Turbine

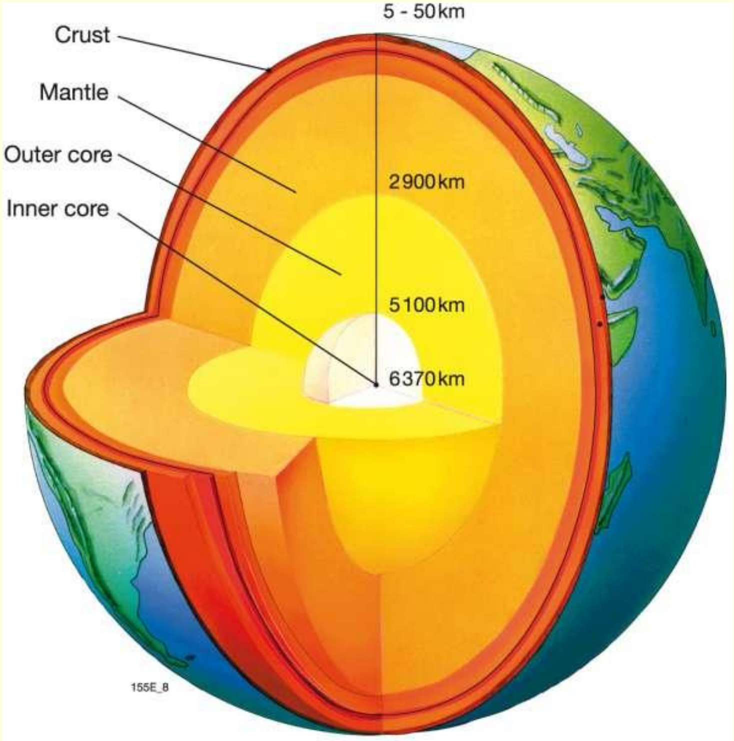
Electricity production from renewables: geothermal



Geothermal

- Geothermal energy is generated in the Earth's core. Temperatures hotter than the sun's surface are continuously produced inside the Earth by the slow decay of radioactive particles. The Earth has a number of different layers:

  - A solid inner core and an outer core made of magma (melted rock)
  - The mantle, made up of magma and rock, surrounds the core and is about 1,800 miles thick.
  - The crust is the outermost layer of the Earth, the land that forms the continents and ocean floors. The crust is 15 - 35 miles thick.



Geothermal

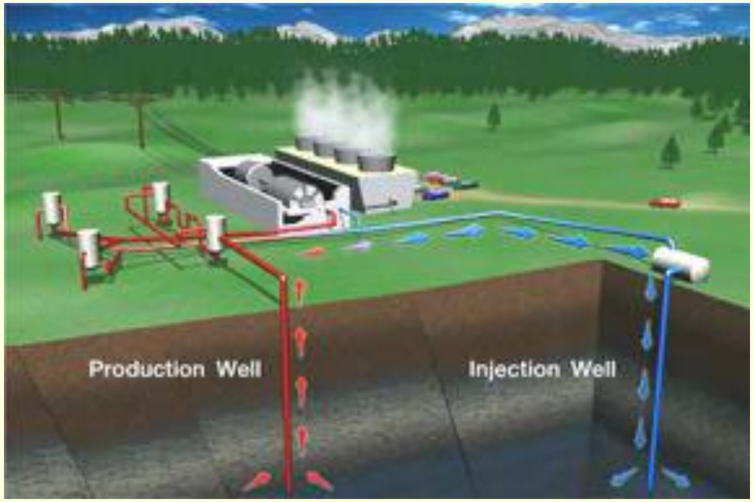
- Naturally occurring large hydrothermal resources are called **geothermal reservoirs**. Most geothermal reservoirs are deep underground. But geothermal energy sometimes finds its way to the surface in the form of **volcanoes, hot springs** and **geysers.**
- In some cases, geothermal energy is used directly to heat city districts by digging wells and pumping the heated water or steam to the surface. For example, district heating system provides heat for 95% of the buildings in Reykjavik, Iceland.

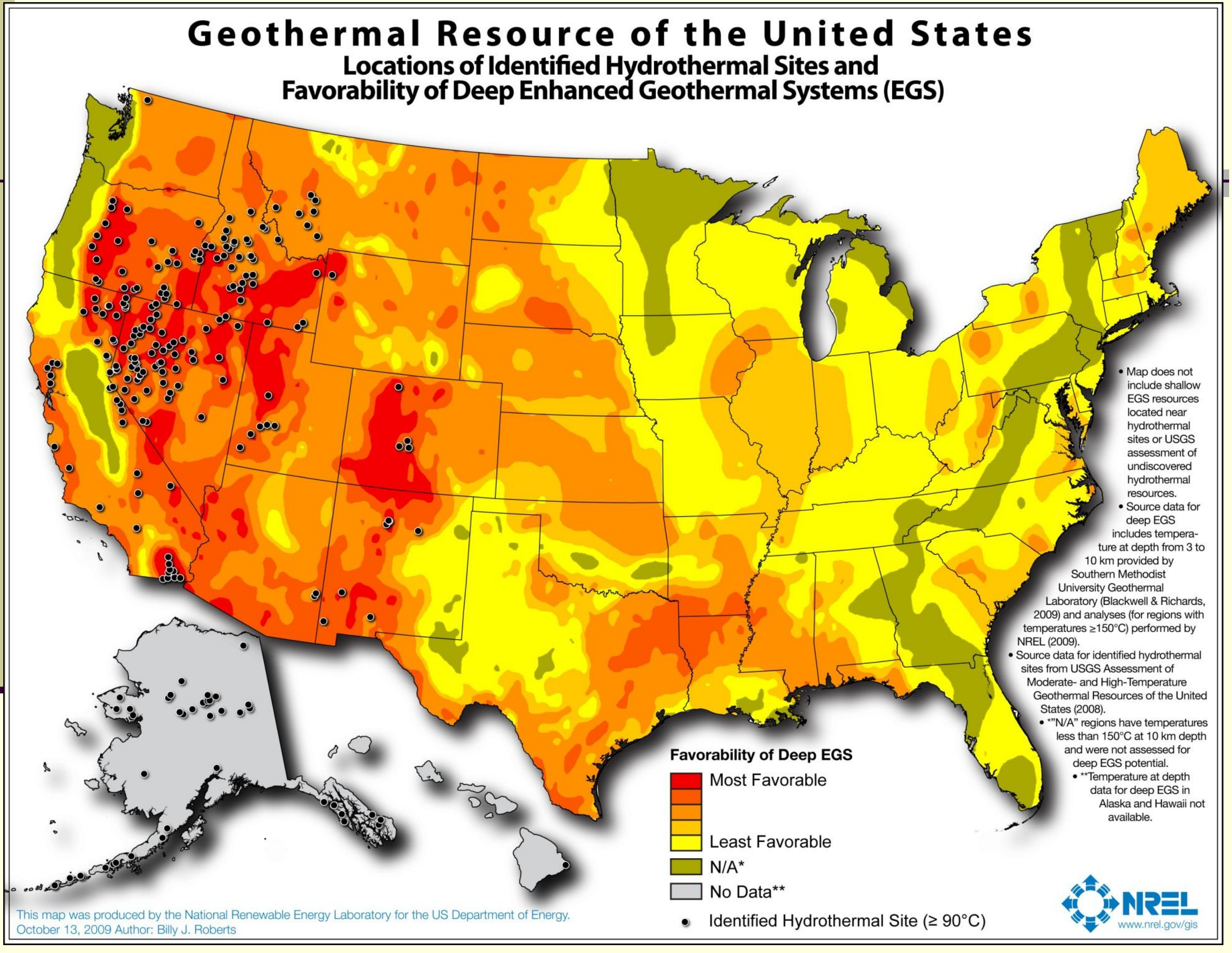


Geothermal

- **Dry steam plants** use steam piped directly from a geothermal reservoir to turn the generator turbines. The first geothermal power plant was built in 1904 in Tuscany, Italy.

- **Flash steam plants** take high-pressure hot water from deep inside the Earth and convert it to steam to drive the generator turbines. When the steam cools, it condenses to water and is injected back into the ground to be used over and over again.




Geothermal Resource of the United States
Locations of Identified Hydrothermal Sites and
Favorability of Deep Enhanced Geothermal Systems (EGS)
• Map does not include shallow EGS resources located near hydrothermal sites or USGS assessment of undiscovered hydrothermal resources.
• Source data for deep EGS includes temperature at depth from 3 to 10 km provided by Southern Methodist University Geothermal Laboratory (Blackwell & Richards, 2009) and analyses (for regions with temperatures ≥150°C) performed by NREL (2009).
• Source data for identified hydrothermal sites from USGS Assessment of Moderate- and High-Temperature Geothermal Resources of the United States (2008).
• *"N/A" regions have temperatures less than 150°C at 10 km depth and were not assessed for deep EGS potential.
• **Temperature at depth data for deep EGS in Alaska and Hawaii not available.
Favorability of Deep EGS
Most Favorable
Least Favorable
N/A*
No Data**
Identified Hydrothermal Site (≥ 90°C)
NREL
www.nrel.gov/gis
This map was produced by the National Renewable Energy Laboratory for the US Department of Energy.
October 13, 2009 Author: Billy J. Roberts

Top Counties with Geothermal Resources

Geothermal electricity production		Geothermal direct use	
Country	GWh/yr	Country	GWh/yr*
United States	16 603	China	20 932
Philippines	10 311	United States	15 710
Indonesia	9 600	Sweden	12 585
Mexico	7 047	Turkey	10 247
Italy	5 520	Japan	7 139
Iceland	4 597	Norway	7 000
New Zealand	4 055	Iceland	6 768
Japan	3 064	France	3 592
Kenya	1 430	Germany	3 546
El Salvador	1 422	Netherlands	2 972
Costa Rica	1 131	Italy	2 762
Turkey	490	Hungary	2 713
Papua New Guinea	450	New Zealand	2 654
Russia	441	Canada	2 465
Nicaragua	310	Finland	2 325

Source: OECD/IEA, 2010

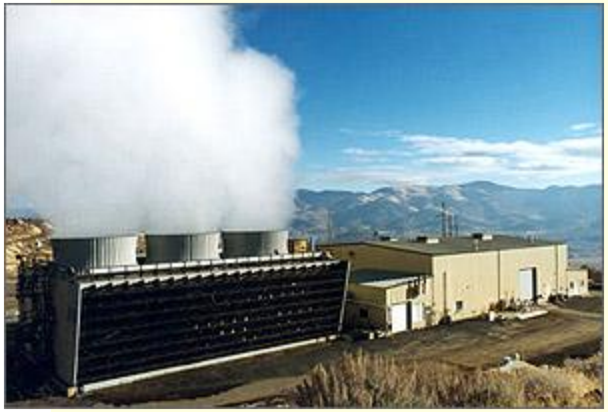
Geothermal in Nevada:

Current Capacity: 385 MW
(+ 150 MW in construction or development stage).

GEOTHERMAL

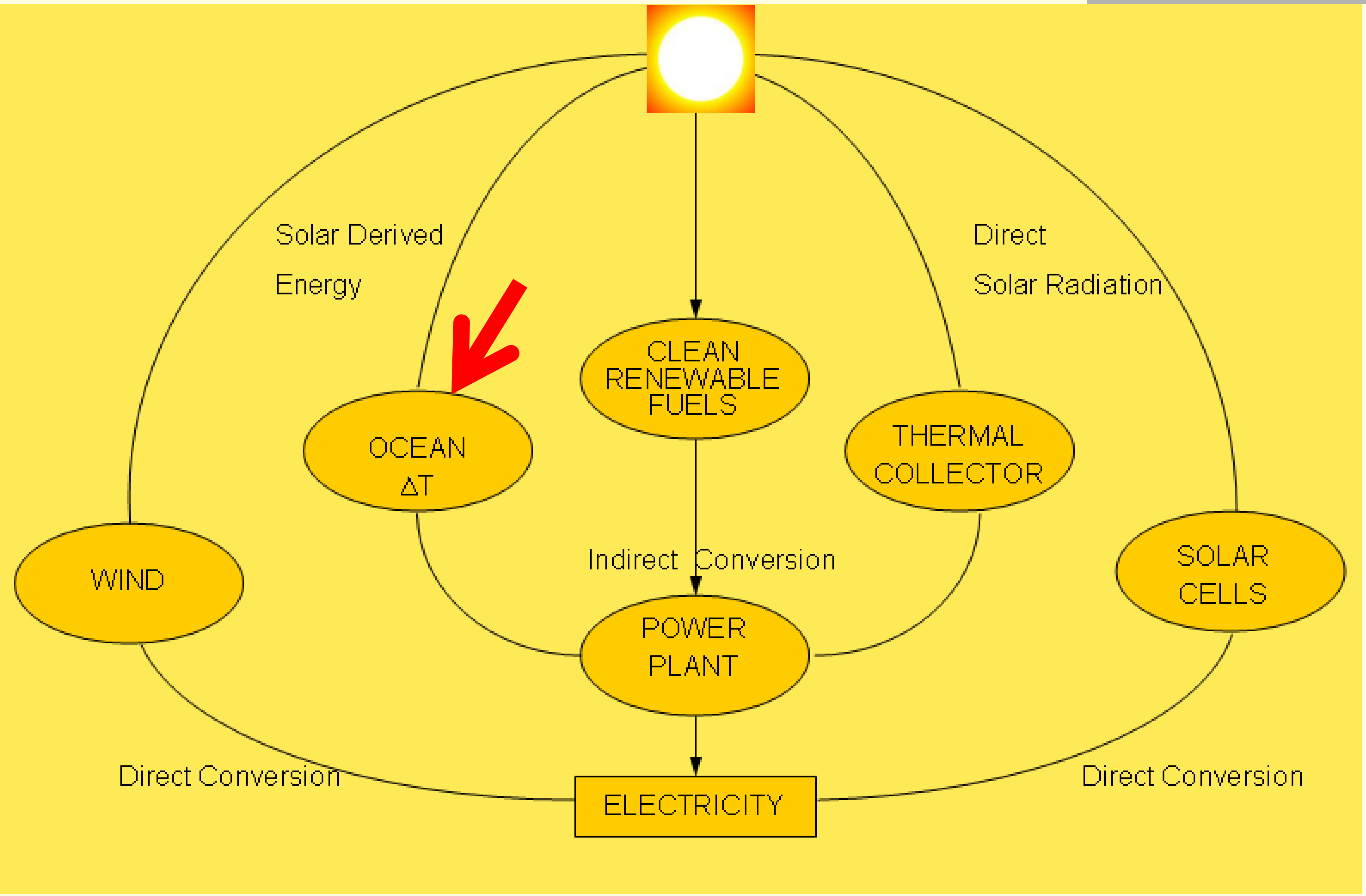
1. Beowawe Power
17.7 MW
2. Brady Geothermal Project
24.0 MW
3. Clayton Valley 1
● 53.5 MW
4. Desert Peak Geothermal Project #2
25.0 MW
5. Dixie Meadows
● 51.0 MW
6. Faulkner 1
49.5 MW
7. Galena 2
13.0 MW
8. Galena 3
26.5 MW
9. Homestretch
2.1 MW
10. Jersey Valley Geothermal Project
22.5 MW
11. McGinness Hills
48.0 MW
12. Richard Burdette Generation Facility
26.0 MW
13. Salt Wells
23.6 MW
14. San Emidio
11.8 MW
15. Soda Lake I
3.6 MW
16. Soda Lake II
19.5 MW
17. Steamboat Hills
14.6 MW
18. Steamboat IA
2.0 MW
19. Steamboat II
13.4 MW
20. Steamboat III
13.4 MW
21. Stillwater 2
47.2 MW
(Photovoltaic Addition 22.0 MW)
22. Tuscarora (aka Hot Sulfur Springs 2)
32.0 MW

● In development or in construction



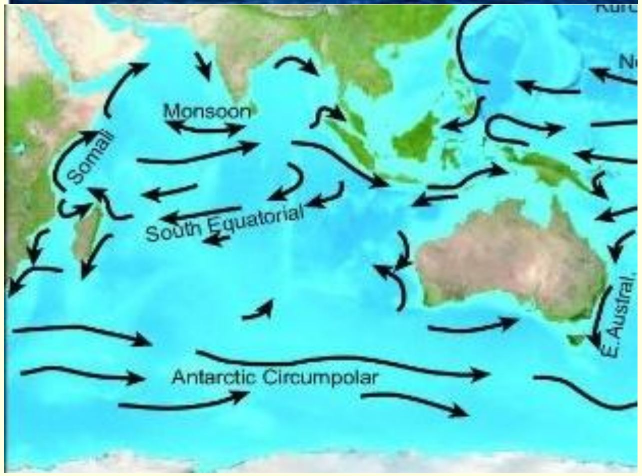
Source: NV Energy Website

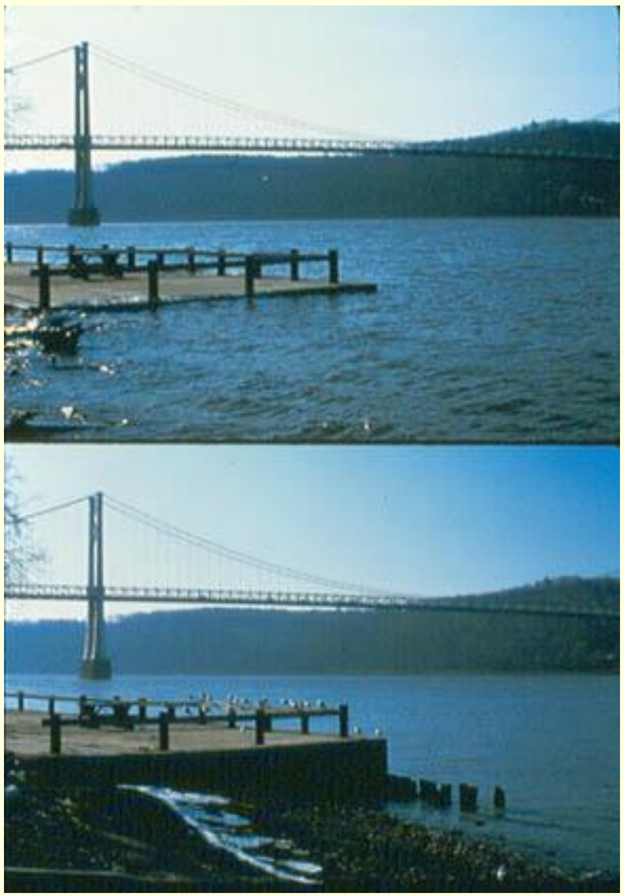
Electricity production from renewables: Ocean power



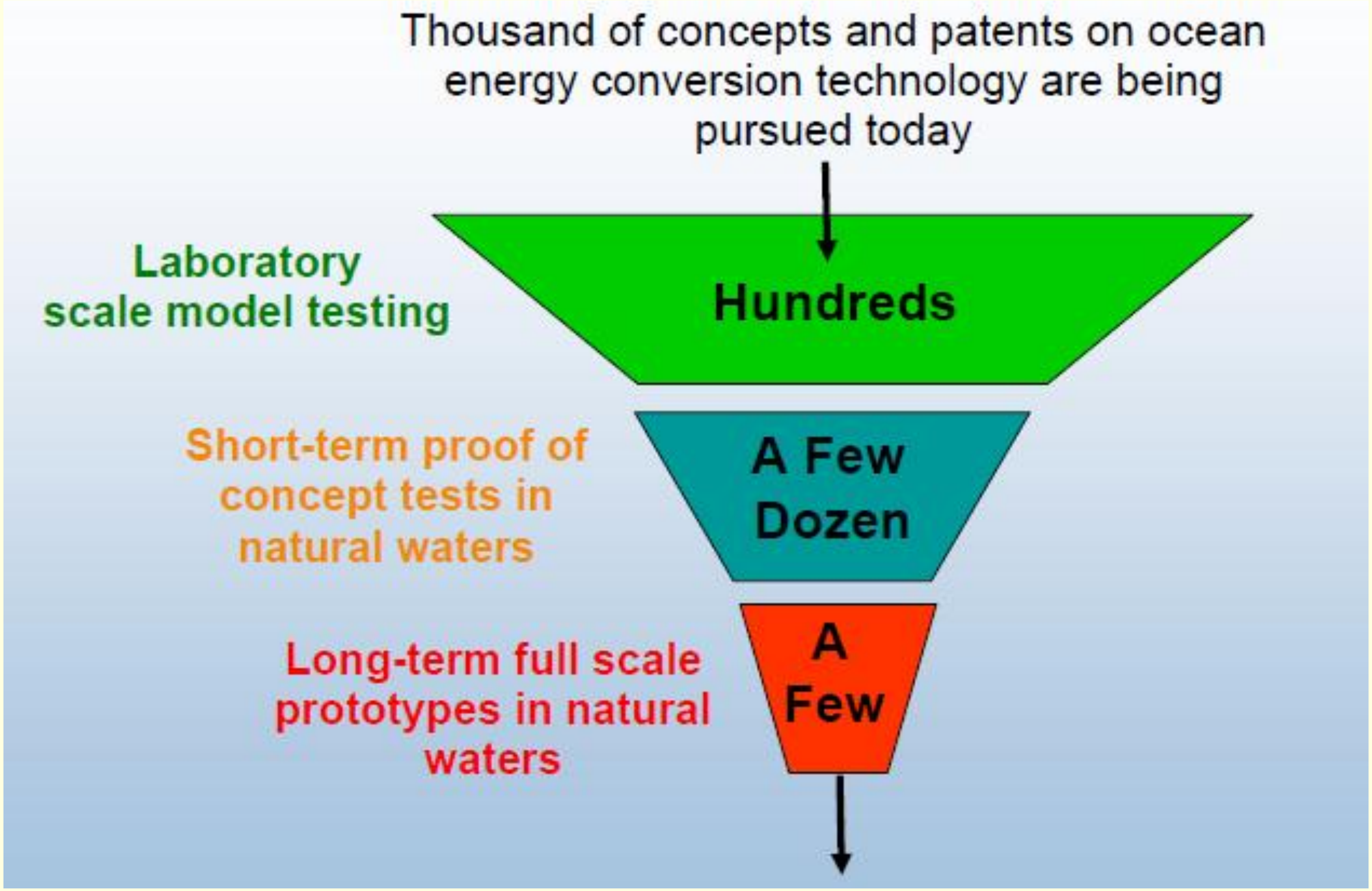
Ocean Power

- Energy can be extracted from the power of the waves, from the tide, or from ocean currents





Ocean power – technology development status



Ocean Power - Waves

- Solar energy creates uneven temperatures and pressures across the globe. This results in wind blowing from high pressure to low pressure areas. When wind comes in contact with the ocean surface, it creates waves.
- Power of a wave per meter of distance along the ridge of the wave (under ideal sinusoidal conditions):

$$P = \frac{\rho g^2 H^2 T}{32\pi}$$

  - ρ: density of sea water (1,025 kg/m^3)
  - g: gravitational acceleration (9.81 m/s^2)
  - H: wave height (m)
  - T: wave period (s)

Scatter Diagram of Wave Energy

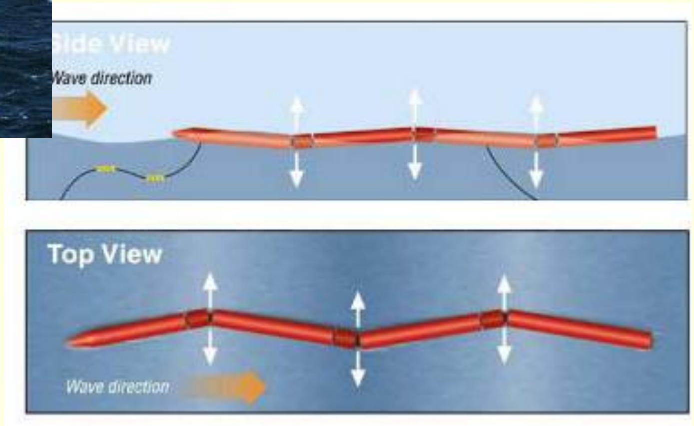
- Both wave height H and wave period are variable.
- The annual energy is calculated by multiplying the hours per year for each sea state (H,T) by the power at that state and summing the results.

Significant Wave Height [m] \ Energy Period [s]	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
10																	0.11	
9.5																0.14	0.05	
9																0.04	0.13	
8.5																0.11	0.15	
8													0.11			0.13	0.20	
7.5										0.04			0.09	0.02	0.16	0.31	0.26	0.06
7										0.06	0.03	0.06	0.12	0.06	0.18	0.63	0.51	
6.5								0.01	0.09	0.15	0.12	0.10	0.29	0.18	0.56	1.59	0.61	0.07
6								0.01	0.19	0.31	0.12	0.16	0.45	0.37	1.32	1.92	0.85	0.35
5.5								0.07	0.47	0.64	0.32	0.49	0.87	0.76	2.12	2.05	1.05	0.78
5							0.02	0.74	1.12	0.57	0.60	0.88	1.62	1.39	3.11	3.04	1.30	0.96
4.5						0.00	0.30	2.01	1.21	0.82	0.98	1.59	2.67	2.77	3.93	2.69	1.21	1.03
4					0.00	0.10	1.37	2.77	1.04	1.15	1.66	3.31	5.32	3.27	4.68	2.25	0.77	1.18
3.5					0.03	0.60	3.61	2.82	1.23	1.77	3.30	6.59	7.48	4.20	3.53	1.61	0.63	0.82
3				0.00	0.19	2.36	5.53	2.04	1.80	3.45	6.70	9.66	7.30	3.08	2.17	1.38	0.38	0.54
2.5			0.00	0.03	1.12	6.33	4.03	1.86	2.98	5.98	8.81	8.73	4.26	1.50	1.22	0.87	0.22	0.34
2			0.00	0.26	3.69	4.36	2.45	2.97	4.81	6.38	5.62	3.18	1.47	0.69	0.45	0.28	0.09	0.12
1.5			0.03	0.55	1.36	1.49	2.51	2.65	2.10	1.55	0.88	0.45	0.28	0.12	0.10	0.05	0.02	0.02
1		0.00	0.01	0.05	0.10	0.21	0.21	0.10	0.05	0.04	0.03	0.02	0.01	0.00	0.00	0.00		0.00
0.5			0.00	0.00	0.00													0.00

4 Ways to Harness Power from Ocean Waves: attenuators, terminators, point absorbers, and overlapping devices

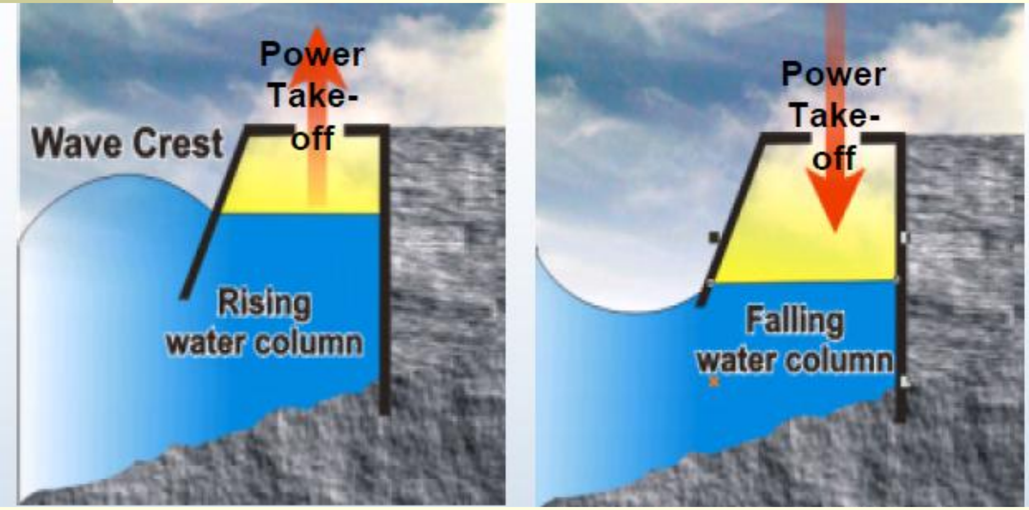
Attenuators: multi-segment floating structures oriented parallel to the direction of the waves. The differing heights of waves along the length of the device causes flexing where the segments connect. This motion is resisted by hydraulic rams which in turn drive electrical generators.

Source: Pelamis Wave Power



Ocean Power - Waves

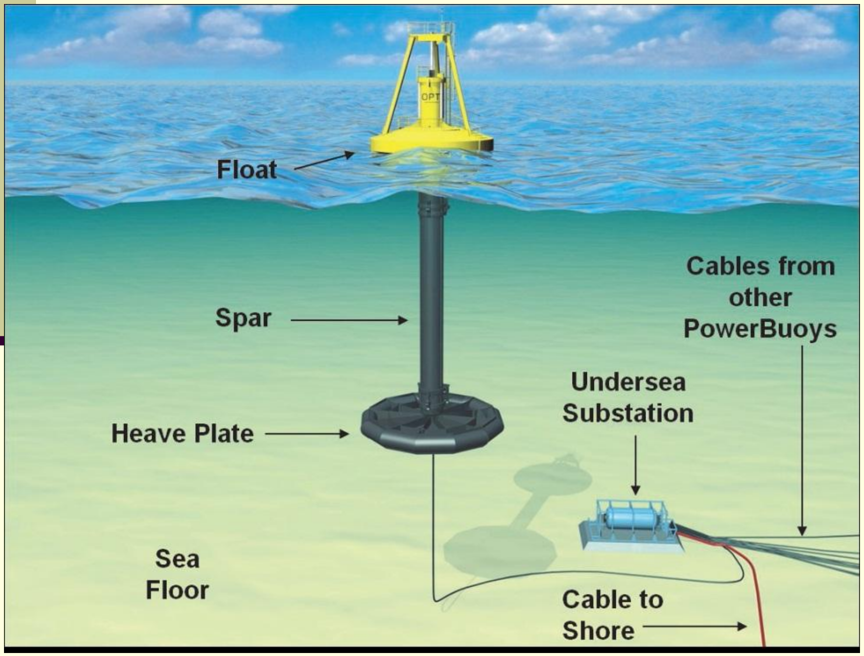
- **Oscillating water column** is a form of terminator in which water enters through a subsurface opening into a chamber with air trapped above it. The wave action causes the captured water column to move up and down like a piston to force the air though an opening connected to a turbine



Source: Oceanlinx, Australia

Ocean Power - Waves

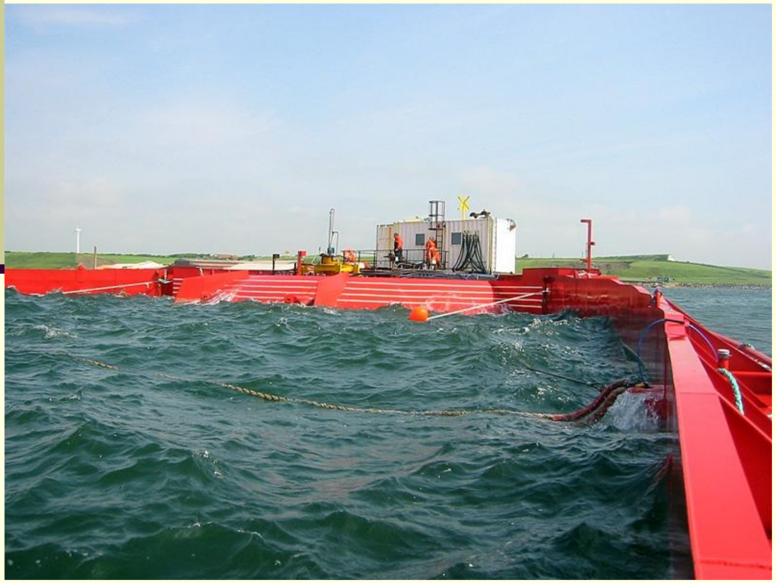
A point absorber is a floating structure with components that move relative to each other due to wave action (e.g., a floating buoy inside a fixed cylinder). The relative motion is used to drive electromechanical or hydraulic energy converters.

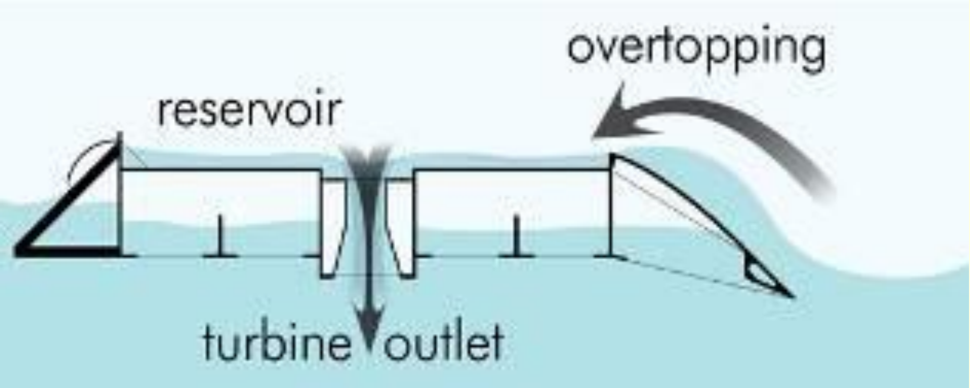


Source: Ocean Power Technologies

Ocean Power - Waves

- **An overtopping device** has reservoirs that are filled by incoming waves to levels above the average surrounding ocean. Gravity causes it to fall back toward the ocean surface. The energy of the falling water is used to turn hydro turbines.





Source: Wave Dragon, Danmark

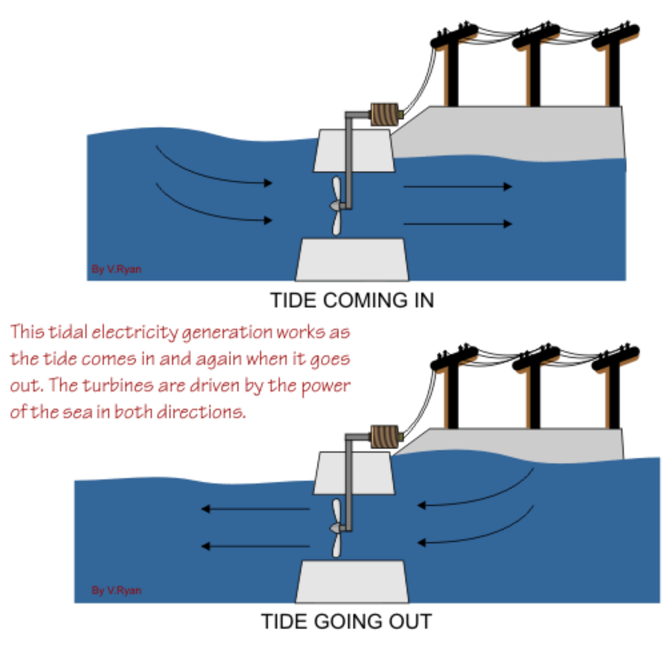
Ocean Cower - Currents

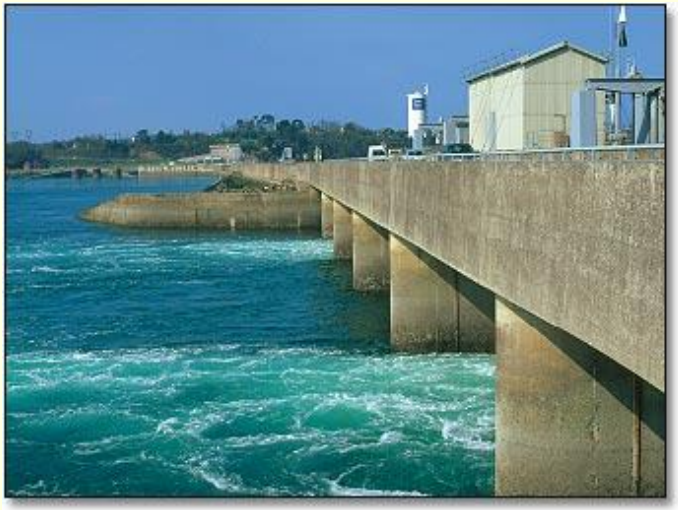
- **Ocean currents** flow in complex patterns affected by the wind, water salinity and temperature, topography of the ocean floor, and gravitational forces exerted by the moon and sun.
- While ocean currents move slowly relative to typical wind speeds, they carry a great deal of energy because of the **density of water** (837 times denser than air). $\mathbf{P = (1/2)\rho A v^3}$
- Many industrialized countries are pursuing ocean current energy. Technical challenges include prevention of marine growth buildup, and corrosion resistance.

Ocean current power station in Northern Ireland (1.2 MW)

Ocean power - Tide

- The tides are the result of the gravitational attraction between the earth and the moon as well as the earth and sun. The strength of the tide is greatly dependent on the earth-moon system.
- Depending on the location and time of year, one can experience two equal tidal cycles (semidiurnal), on tidal cycle (diurnal) or two unequal tidal cycles (mixed tide).
- Enormous volumes of water rise and fall with the tides each day, and many coastal areas can take advantage of this free energy.





Tidal power plant in Brittany, France (240 MW)