Renewable Energy I:
Hydro, Geothermal, Wind, and Solar

AOSC 433/633 & CHEM 433

Ross Salawitch

Class Web Site: http://www.atmos.umd.edu/~rjs/class/spr2017

Next three lectures:

Pros and cons of meeting energy needs by means other than combustion of fossil fuel

We'll begin by going over a few Course Logistics

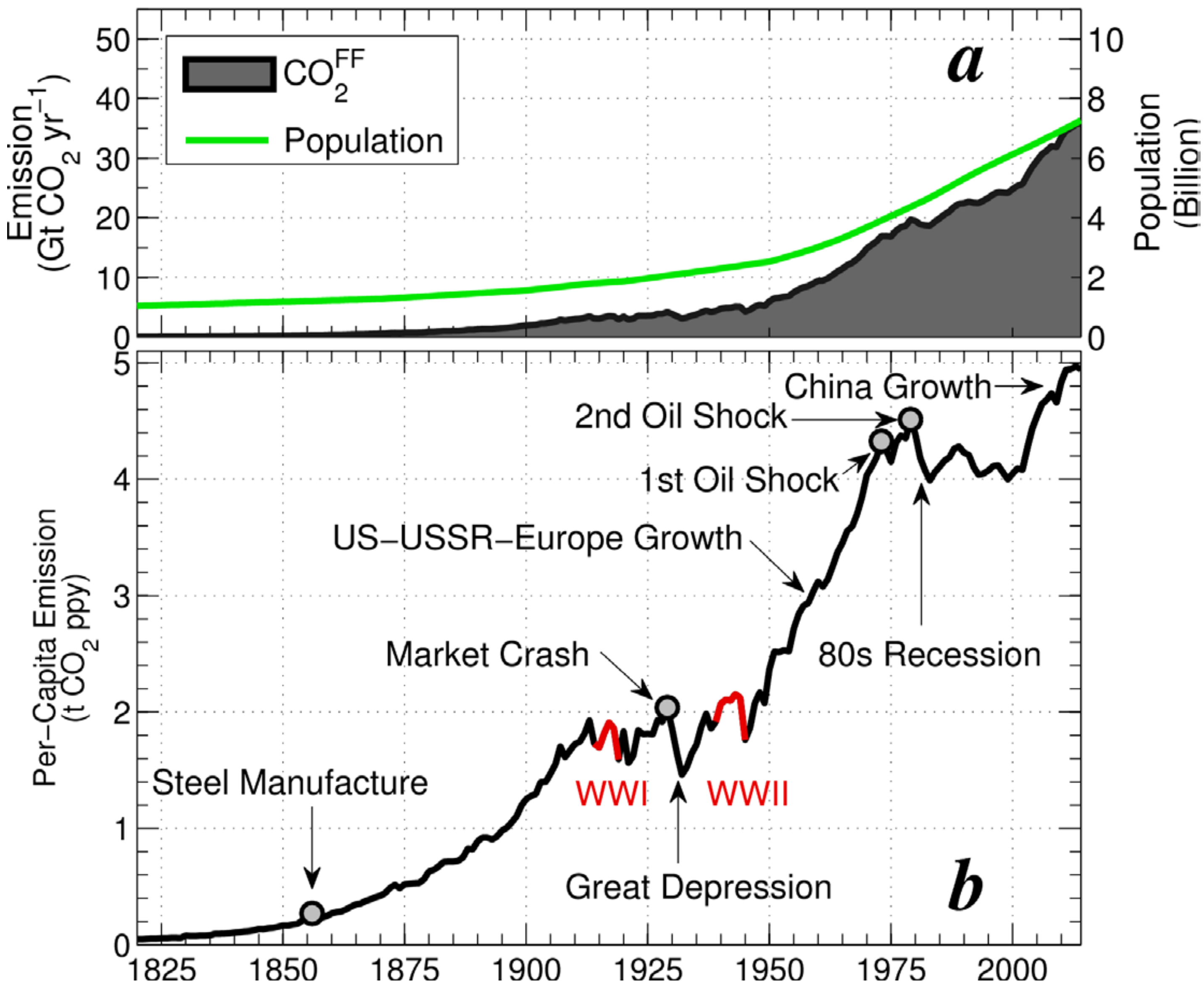
Lecture 19

25 April 2017

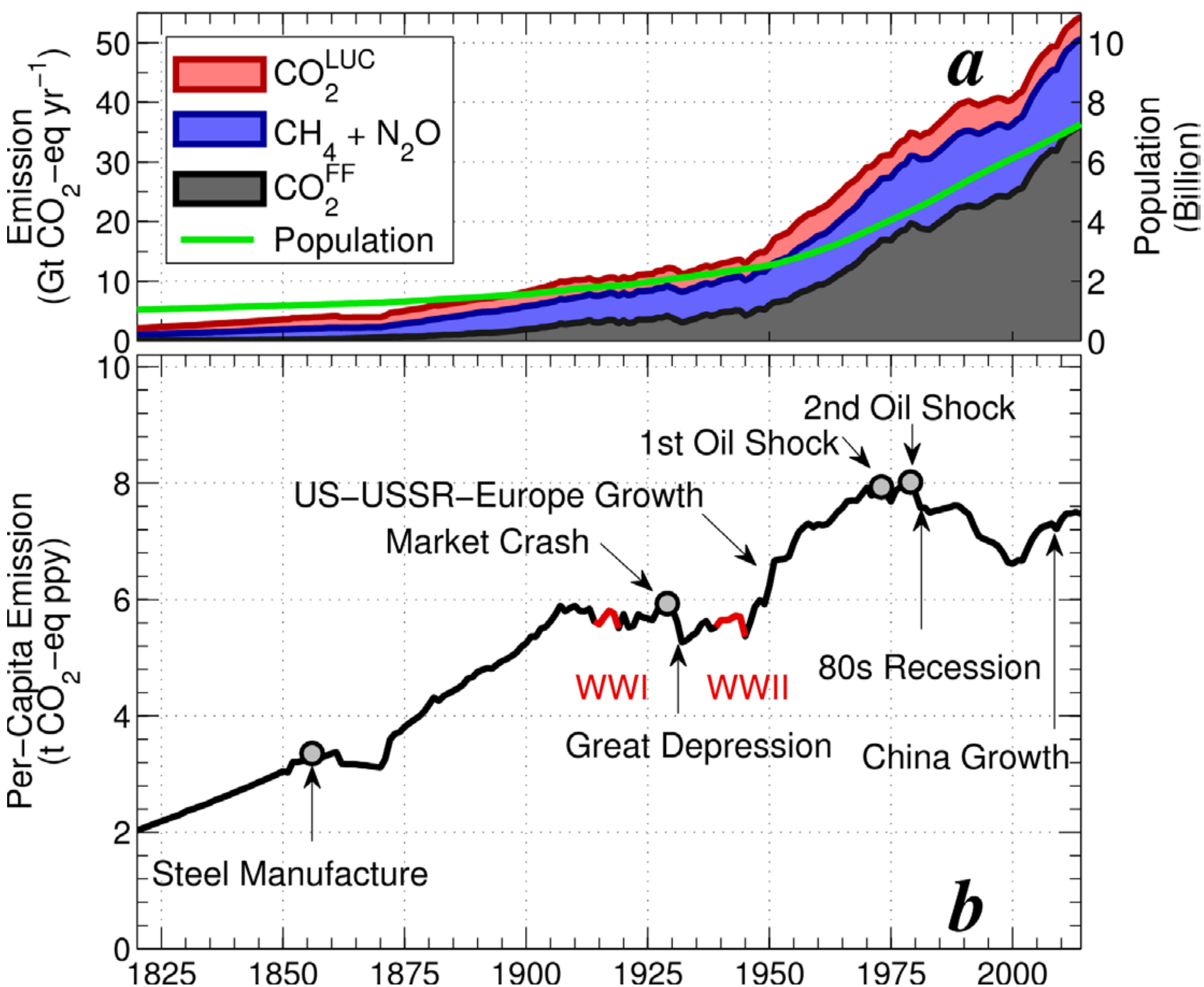
Course Logistics

- Problem Set #4 will be posted by start of class Thursday
  - Due Tues, 9 May (two weeks from today)
  - Of course, last problem set
  - Will conduct review on Wed, 10 May so there will be only 1 day to accept late submissions
- Grad Student Projects:
  - Had presented due date of Wed, 10 May, 6:00 pm in class several times, but website gives due date of Mon, 15 May (which is during finals)
  - Another possibility is Fri, 12 May (Reading Day)
  - Would like super-quick meeting of 633 students immediately after class to finalize due date
  - Delighted to provide comments on either a draft of the paper and/or presentation provided **I have at least 2 days prior to due date**
- Final Exam
  - Wed, 17 May, 10:30 am to 12:30 pm
  - This room
  - Format similar to prior exams
  - Closed book, no notes
  - Slight emphasis on material covered since last exam, but ***entire course*** will be covered on the final exam
  - **Lecture on 11 May 2017 (Thurs) will be a class review/final exam prep**

Follow-up from Tuesday



Follow-up from Tuesday



Nomenclature

Power (energy/time):

TW : Terra Watt; 10^{12} W
GW : Giga Watt; 10^{9} W
MW : Mega Watt; 10^{6} W
kW : Kilo Watt; 10^{3} W

W = 1 joule /sec

Solar arrays are "sized" in terms of kW

Energy (Power $\times$ time):

kW hr : 10^{3} W delivered continuously over an hour
mW hr : 10^{6} W delivered continuously over an hour

Output of solar arrays are metered in terms of kW hr

World Energy & Electricity Supply

World Energy

World Electricity

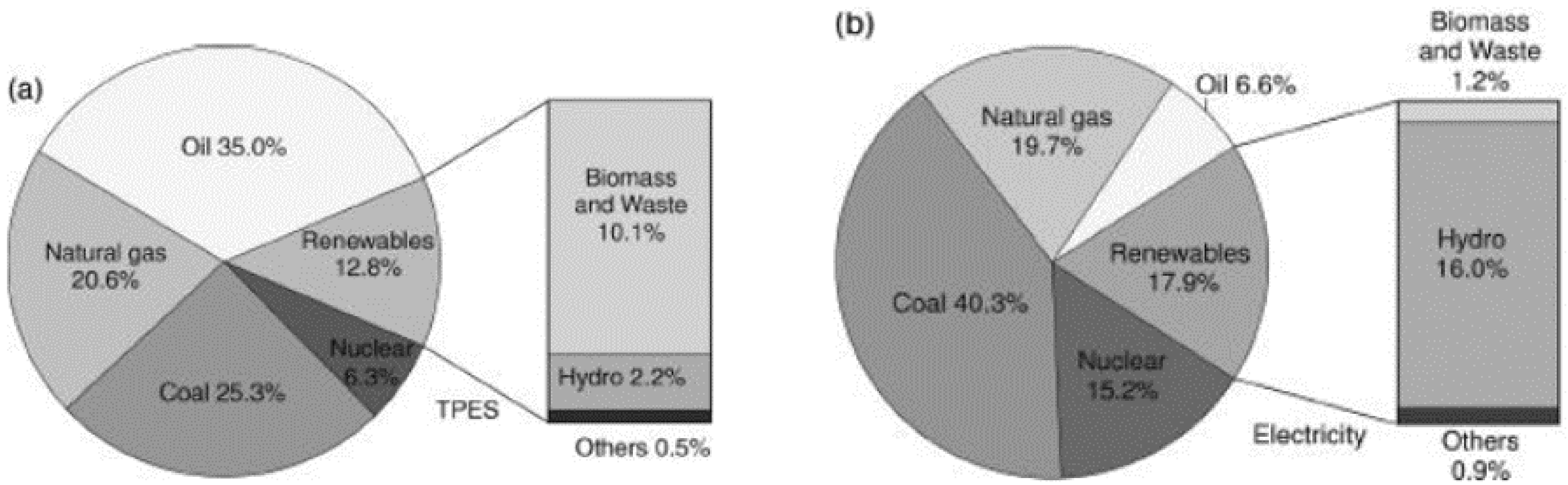


Figure 8.1 (a) Share of renewables in the world total primary energy supply (TPES) in 2005; (b) share of renewables in world electricity production in 2005. (Source: IEA Renewables Information 2007.)

Olah *et al.*, *Beyond Oil and Gas: The Methanol Economy*, 2009

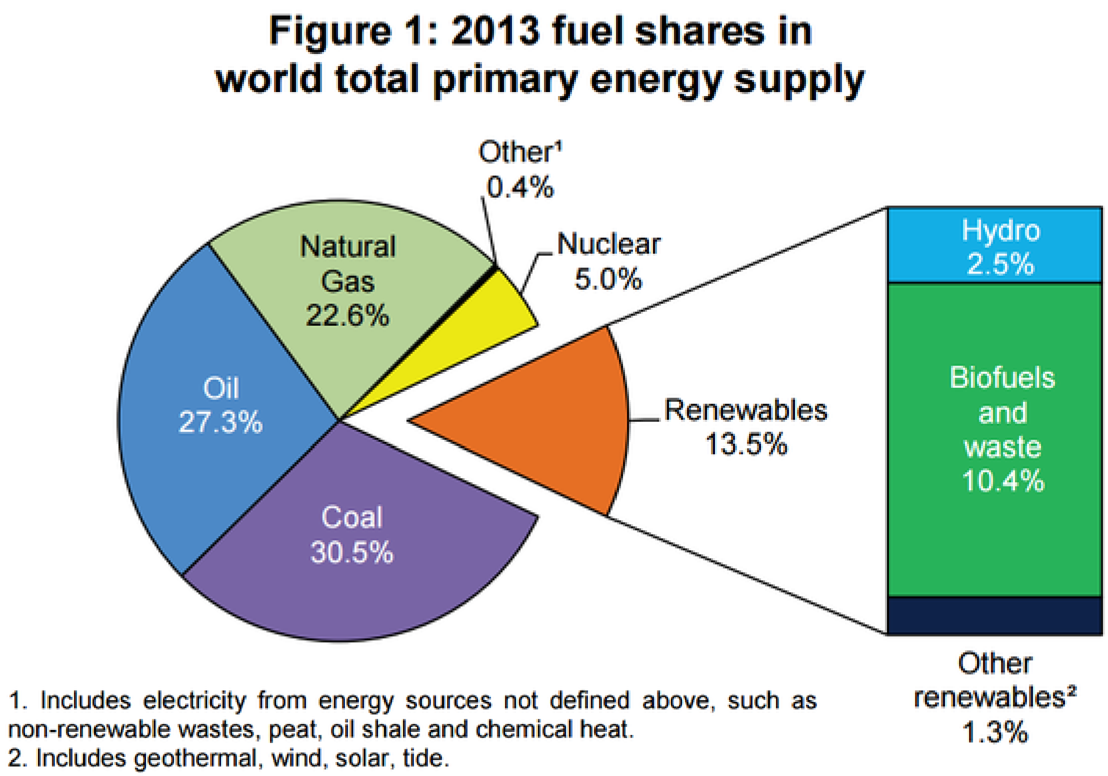
In 2005, world obtained:

~80% of its **energy** &

~66% of its **electricity**

from combustion of fossil fuels

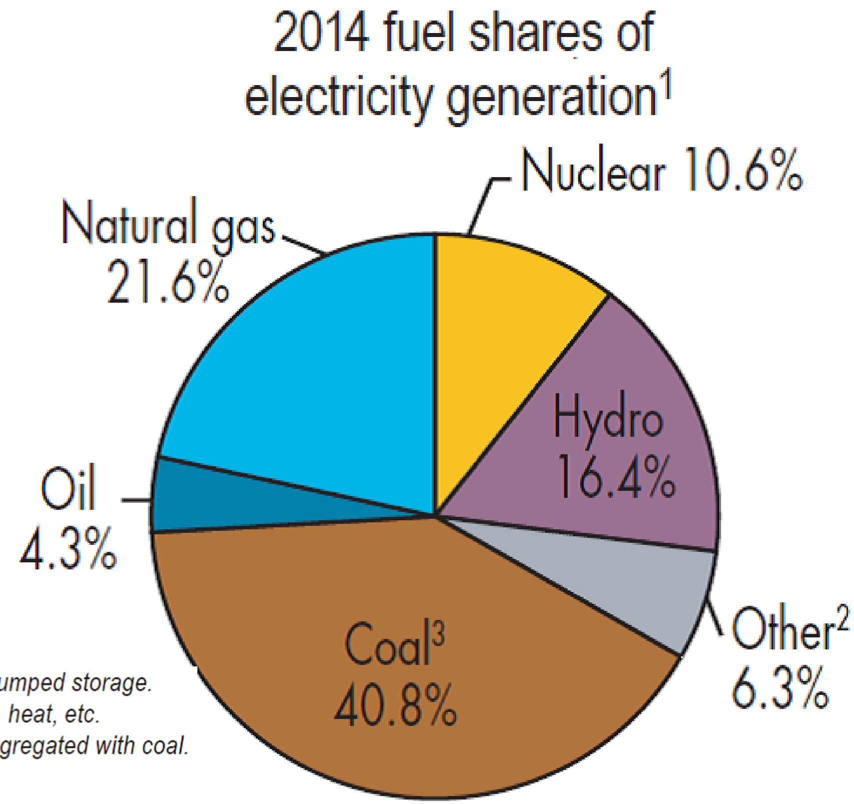
World Energy Update



http://pbs.twimg.com/media/CMEFh00WwAEa-5P.png

In 2013, world still obtained
~80% of its **energy**
from combustion of fossil fuels

World Electricity Update



1. Excludes electricity generation from pumped storage.
2. Includes geothermal, solar, wind, heat, etc.
3. In these graphs, peat and oil shale are aggregated with coal.

https://www.iea.org/publications/freepublications/publication/KeyWorld2016.pdf

In 2014, world still obtained ~67% of its **electricity** from combustion of fossil fuels

World *Electricity* Generating Capacity:

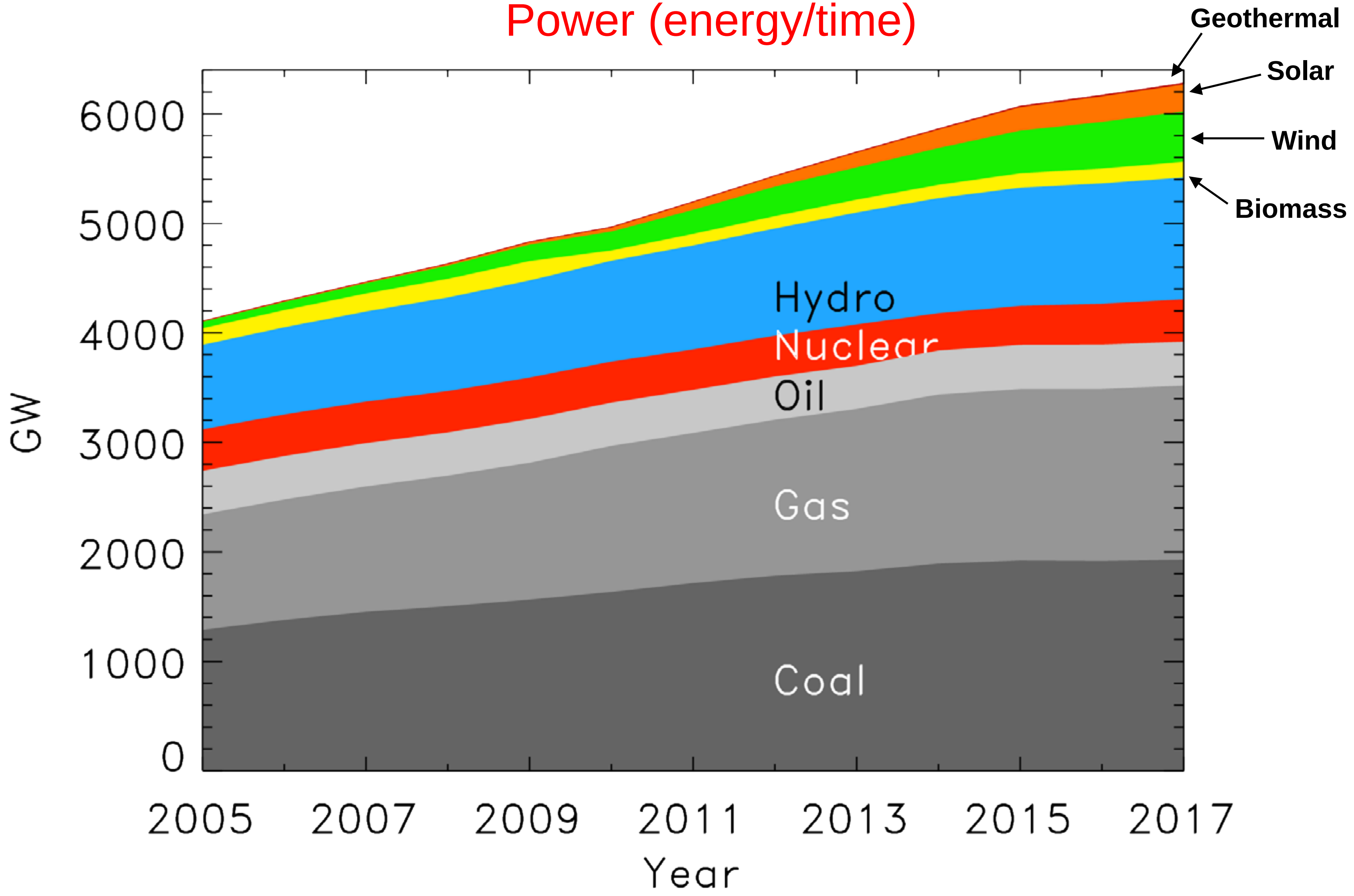
Power (energy/time)

Total Source	GW (year 2017)
Coal	1,928
Natural Gas	1,589
Hydro-electric	1114
Wind	460
Liquid Fossil Fuel	402
Nuclear	386
Solar	247
Other Renewable (Biomass)	142
Geothermal	17
Total	6285

Source: https://www.eia.gov/outlooks/ieo/ieo_tables.cfm

World *Electricity* Generating Capacity:

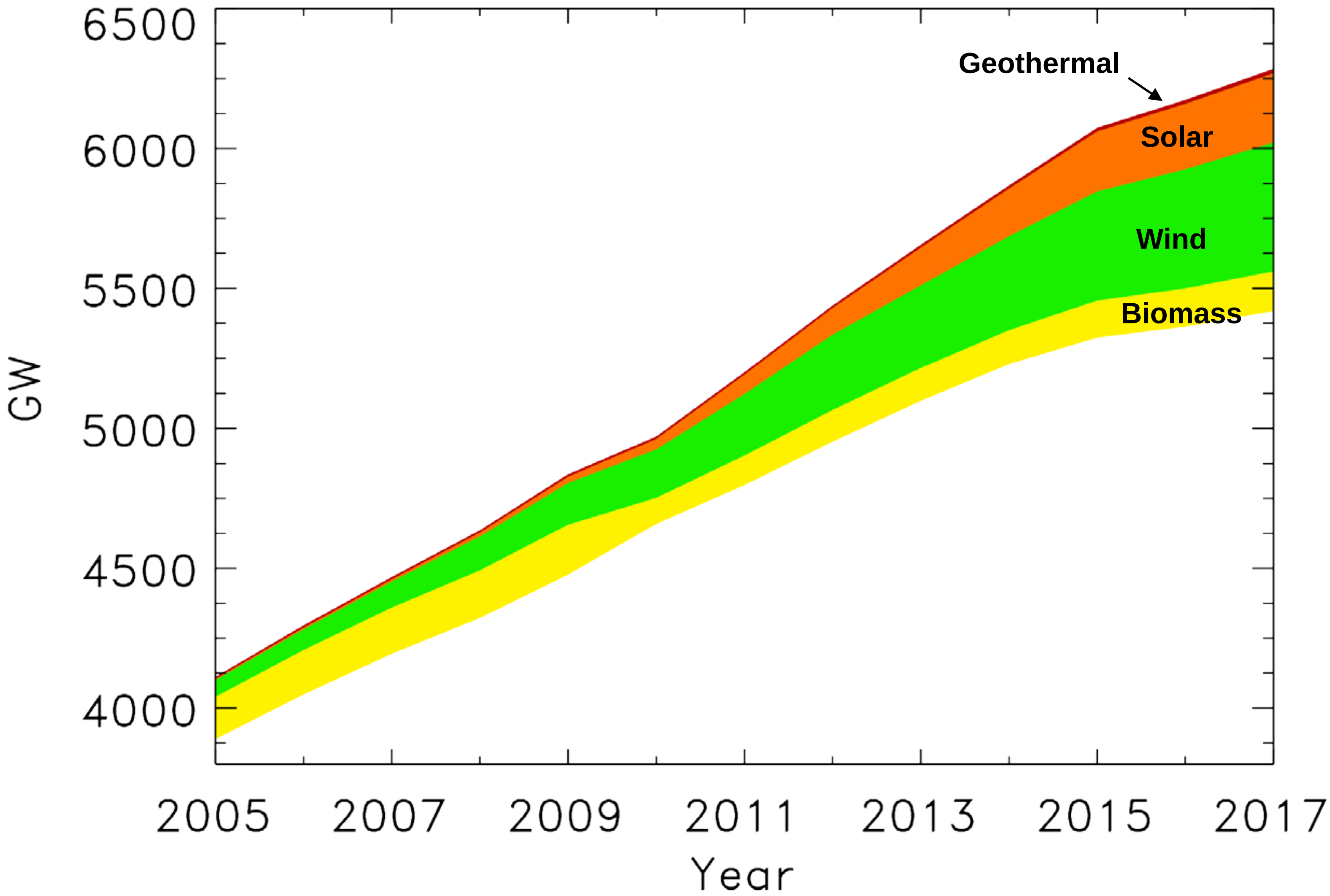
Power (energy/time)



Source: https://www.eia.gov/outlooks/ieo/ieo_tables.cfm

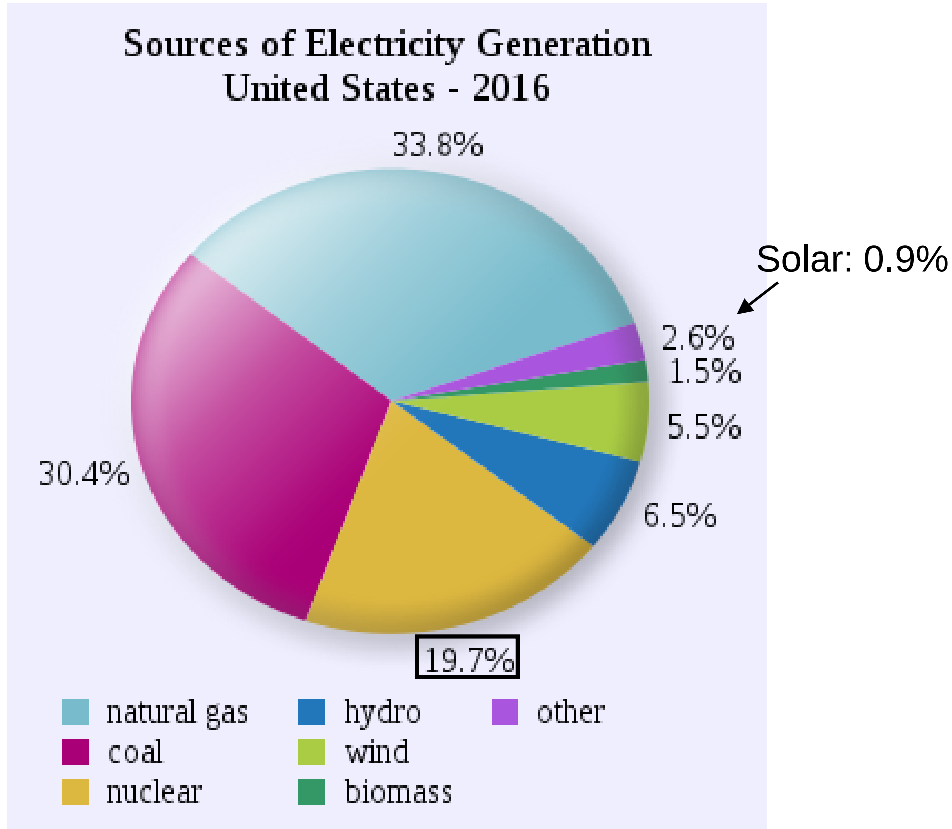
World *Electricity* Generating Capacity:

Power (energy/time)



Source: https://www.eia.gov/outlooks/ieo/ieo_tables.cfm

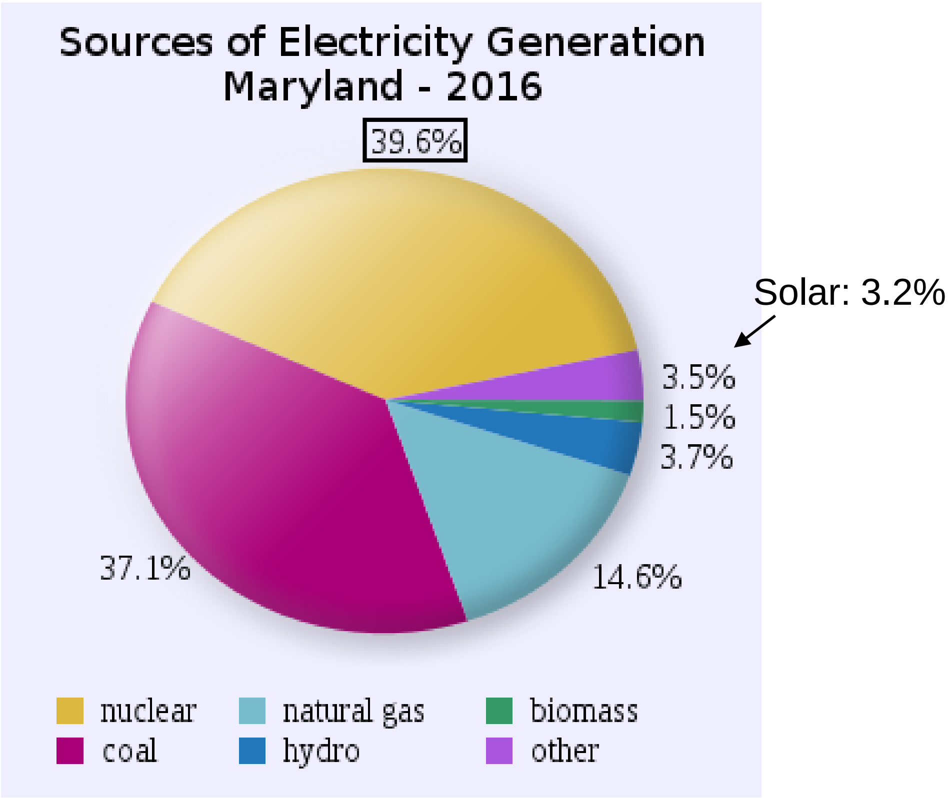
U.S. *Electricity* Supply: 2016



http://www.c2es.org/technology/overview/electricity

U.S. obtains ~64% of its electricity from fossil fuels & ~14% from hydro, wind, biomass, and solar

MD *Electricity* Supply: 2016



https://commons.wikimedia.org/wiki/File:Maryland_Electricity_Generation_Sources_Pie_Chart.svg

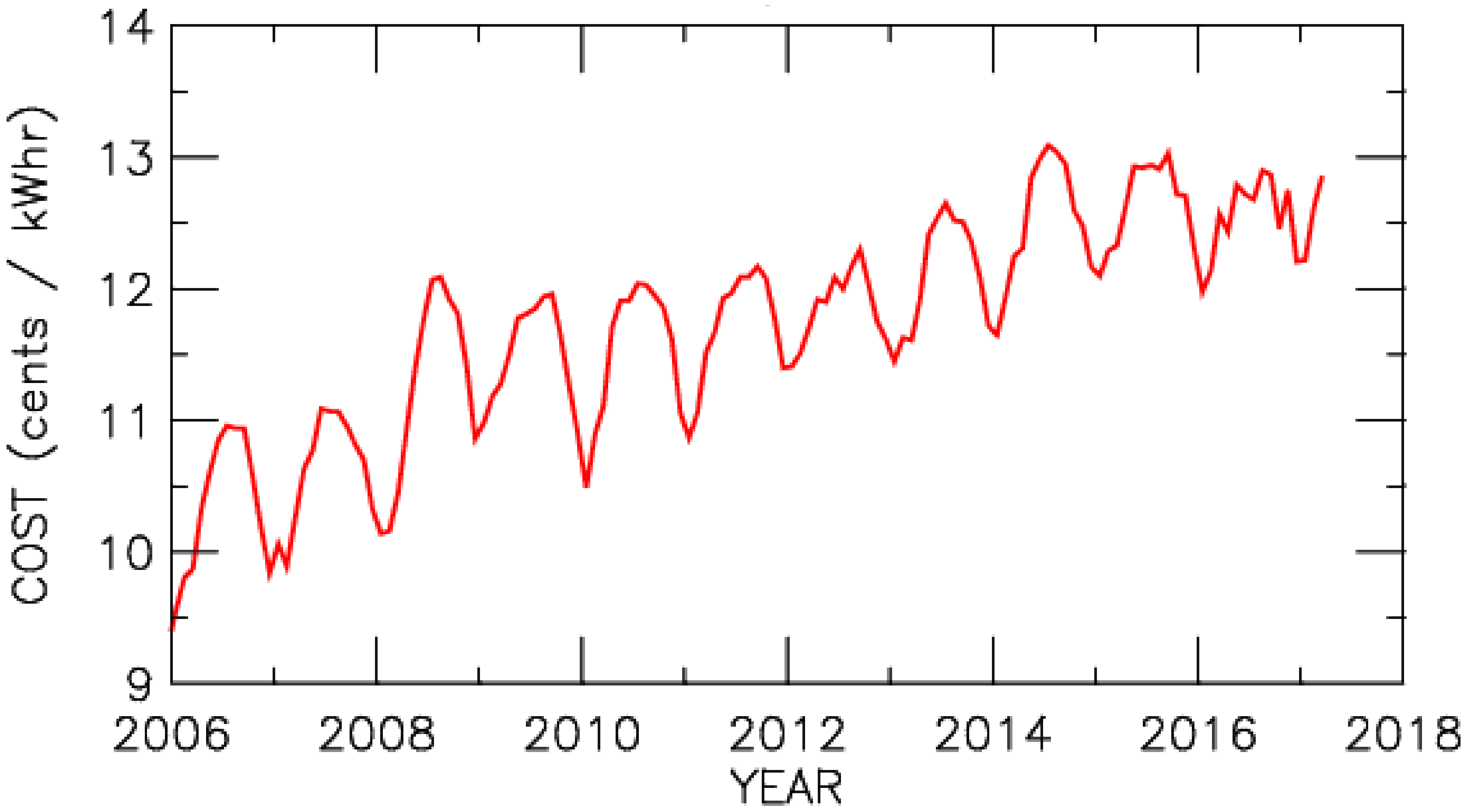
Maryland obtains ~52% of its electricity from fossil fuels & ~9% from hydro, wind, biomass, and solar

Market Force #1: Cost of Fossil Fuel ↑

Crude Oil Price History Chart

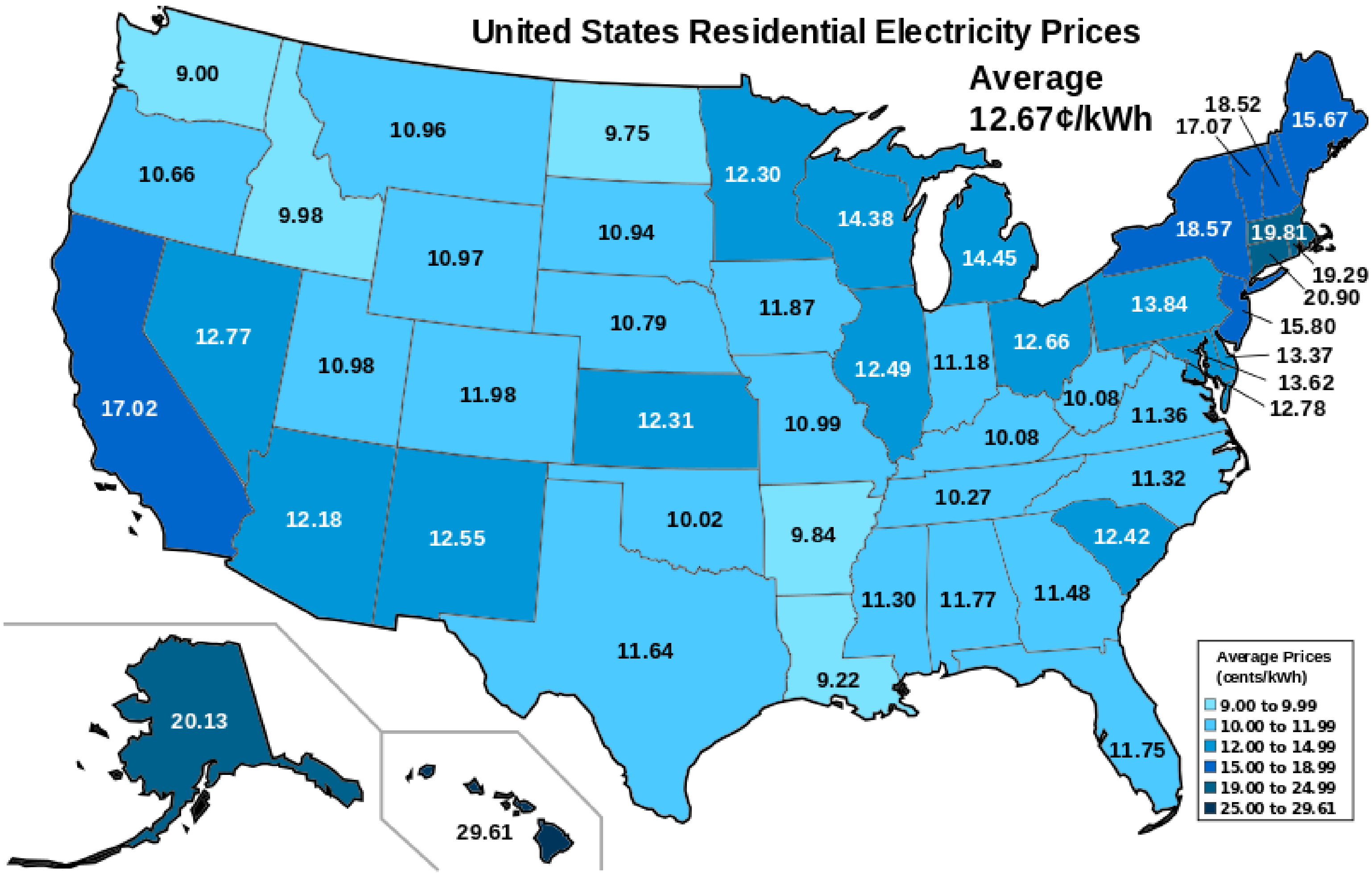
https://mellanosternidag.wordpress.com/2014/12/29/oljepriset/

Residential Electricity Cost, United States



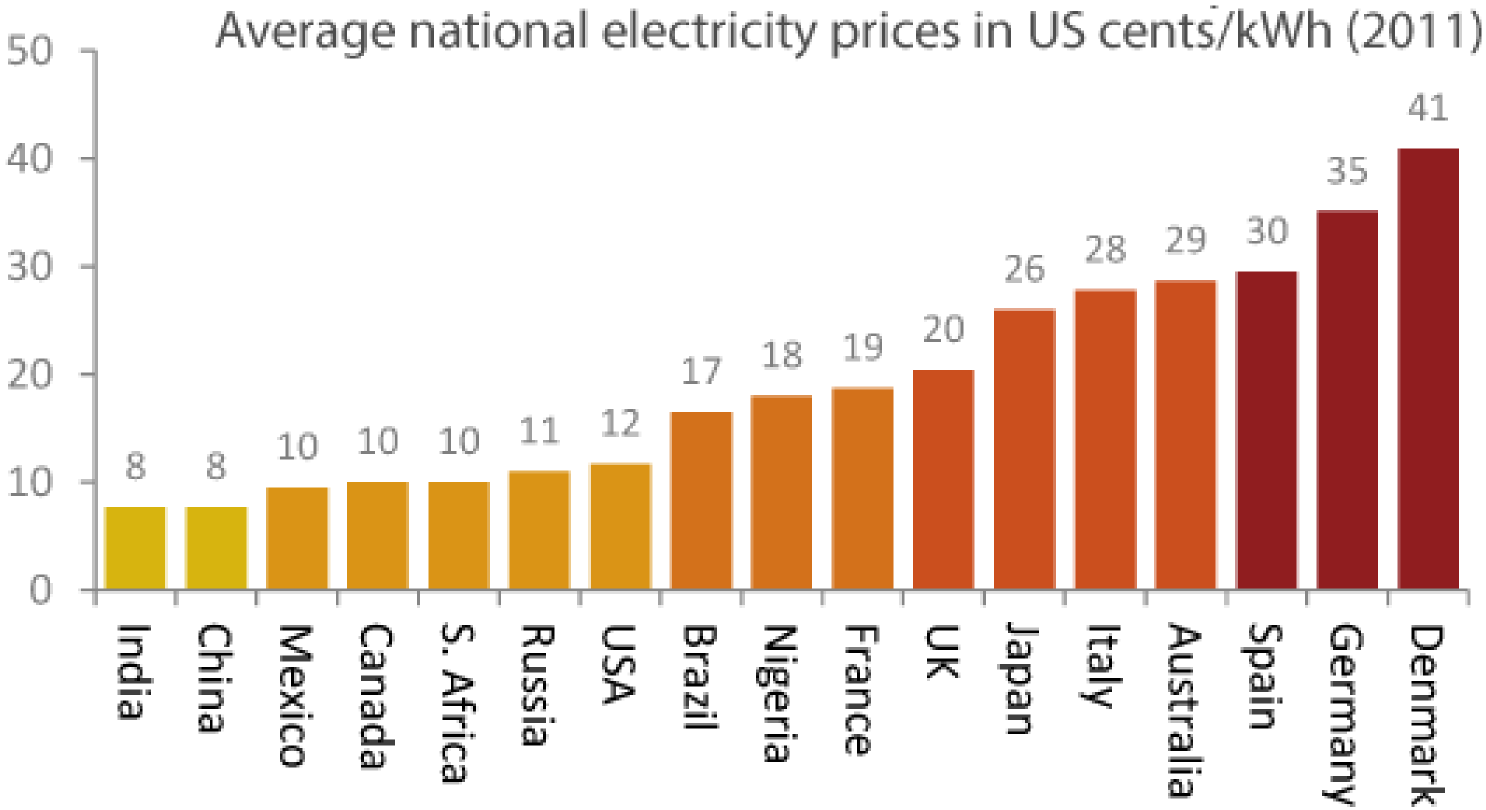
http://www.eia.doe.gov/forecasts/steo/report/electricity.cfm

U.S average residential retail price of electricity: 12.67 cents per kilowatt-hour in 2015



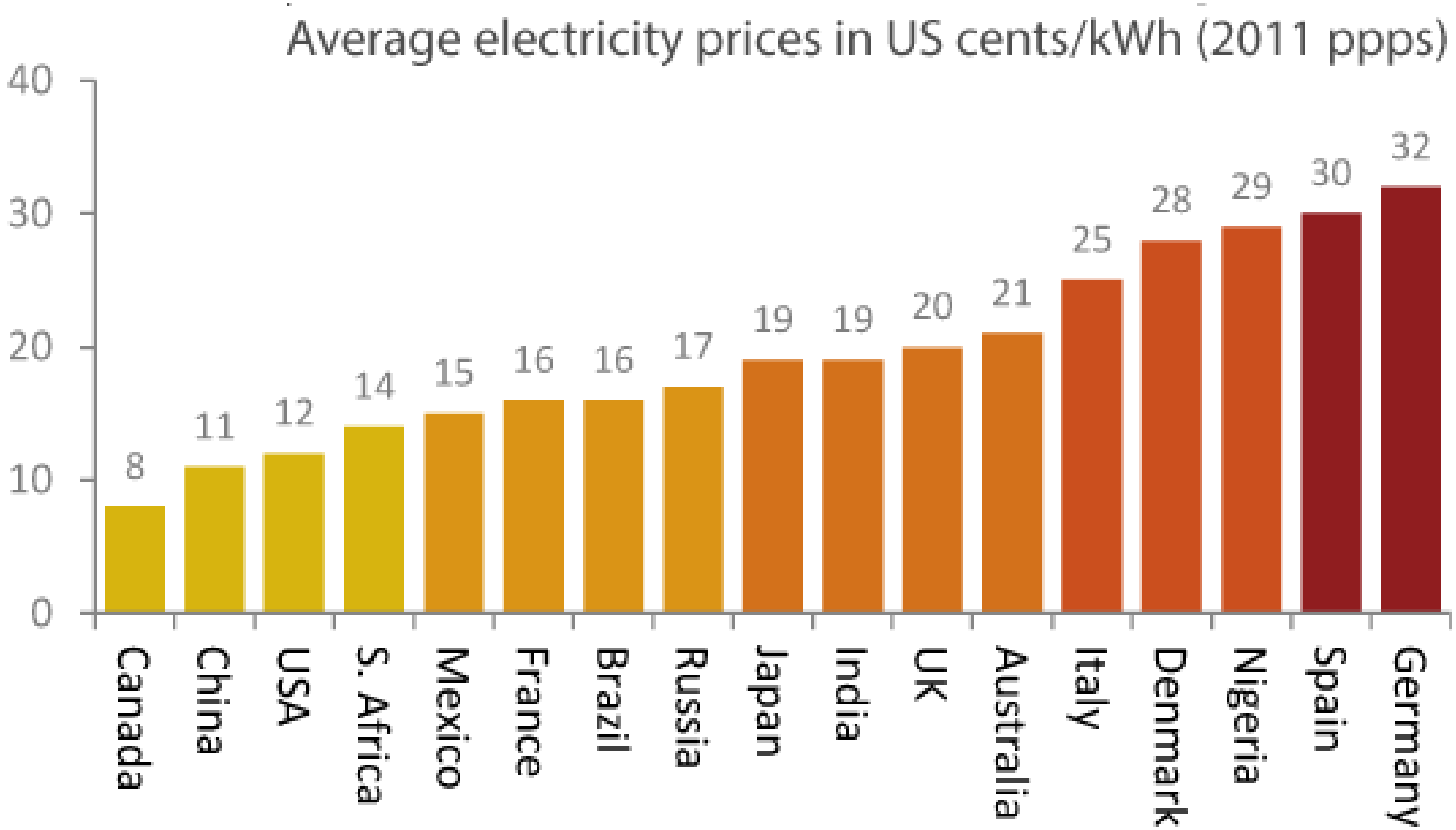
https://commons.wikimedia.org/wiki/File:Average_Residential_Price_of_Electricity_by_State.svg

Price of Electricity varies a lot Internationally



http://theenergycollective.com/lindsay-wilson/279126/average-electricity-prices-around-world-kwh

Price of Electricity varies a lot Internationally

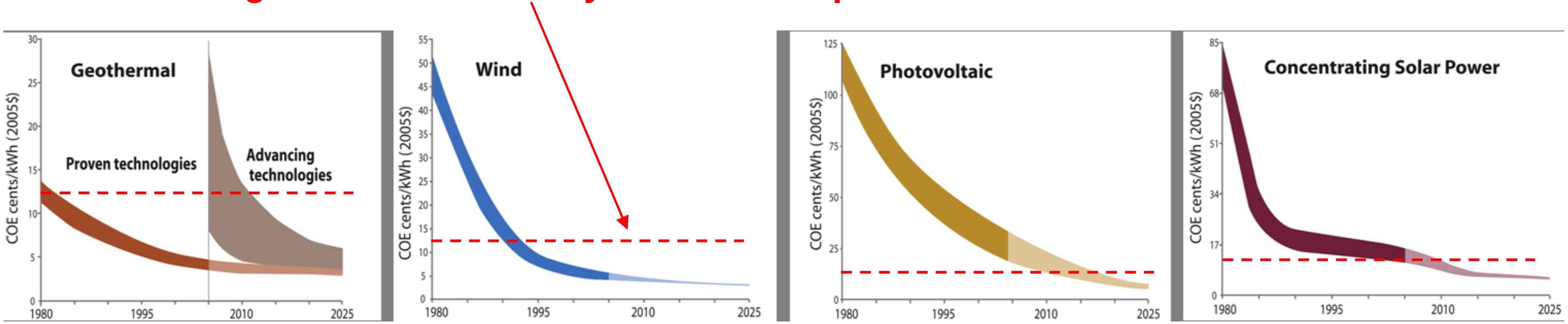


ppps: purchasing power parities

http://theenergycollective.com/lindsay-wilson/279126/average-electricity-prices-around-world-kwh

Market Force #2: Cost of Electricity from Renewables ↓

2015 US Average Cost of Electricity: ~12.7 cents per kw-hour



National Renewable Energy Lab: http://www.nrel.gov/analysis/docs/cost_curves_2005.ppt

Hydro

- World's largest renewable energy source for production of electricity
  - 17% of world's electricity needs
  - Nearly 100% of electricity in Norway, Uruguay, and Paraguay
  - Canada: nearly 50% US: ~7% in 2005 as well as today
- Technology very mature
- Only ~20% of world overall potential being tapped

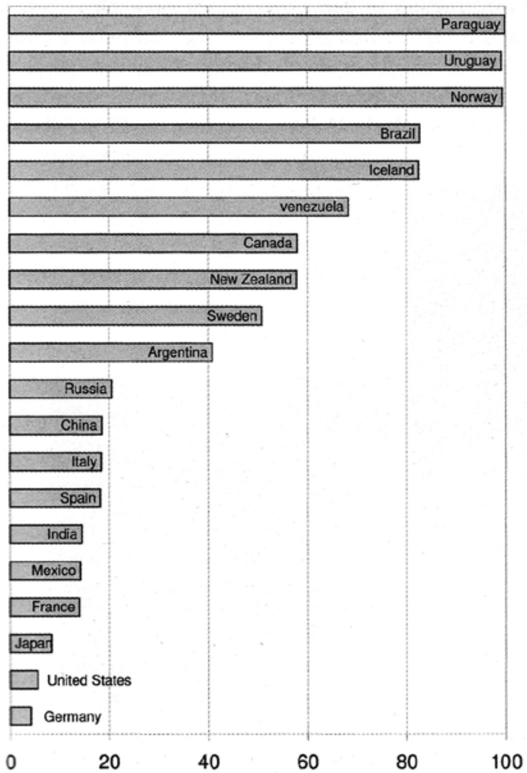


Figure 8.2 Percentage of electricity produced from hydropower in different countries. (Source: CIA World Factbook, December 2003.)

Hydro: 17.7 % of world electricity capacity

Total Source	GW (year 2017)
Coal	1,928
Natural Gas	1,589
Hydro-electric	**1114**
Wind	460
Liquid Fossil Fuel	402
Nuclear	386
Solar	247
Other Renewable (Biomass)	142
Geothermal	17
Total	6285

Olah *et al.*, *Beyond Oil and Gas: The Methanol Economy*, 2009.

Hydro

Typical coal plant: 670 MW
Typical nuclear plant: 1000 MW

Largest Capacities:

- Itaipú, Paraná River, South America: 14,000 MW
  - Built 1975 to 1991
  - Volume of iron and steel: enough to build 380 Eiffel Towers
  - Volume of concrete :15 × that of Channel Tunnel between France and England

Itaipú Dam, Paraguay/Brazil. The world's largest hydroelectric facility.
Credit: Itaipu Binacional

second

http://ga.water.usgs.gov/edu/hybiggest.html

- Three Gorges Dam, Yangtze River, China: 22,500 MW
  - Fully operational in 2012
  - Cost: $22.5 billion or 1 million $ / MW
  - Largest construction project in China since Great Wall
  - 1 million people displaced
  - Now provides ______ of China's electricity needs

Source: http://en.wikipedia.org/wiki/Three_Gorges_Dam

Hydro

Annual Production of Electricity, Three Gorges Dam

Year	Number of installed units	TWh	
2003	6	8.607	
2004	11	39.155	
2005	14	49.090	
2006	14	49.250	
2007	21	61.600	
2008	26	80.812	[54]
2009	26	79.470	[55]
2010	26	84.370	[56]
2011	29	78.290	[57]
2012	32	98.100	[58]
2013	32	83.270	[59]
2014	32	98.800	[60]
2015	32	87.000	[61]
2016	32	93.500	

In 2012, the Three Gorges Dam in China took over the #1 spot of the largest hydroelectric dam (in electricity production), replacing the Itaipú hydroelectric power plant in Brazil and Paraguay.

Three Gorges Dam has a generating capacity of 22,500 megawatts (MW) compared to 14,000 MW for the Itaipú Dam.

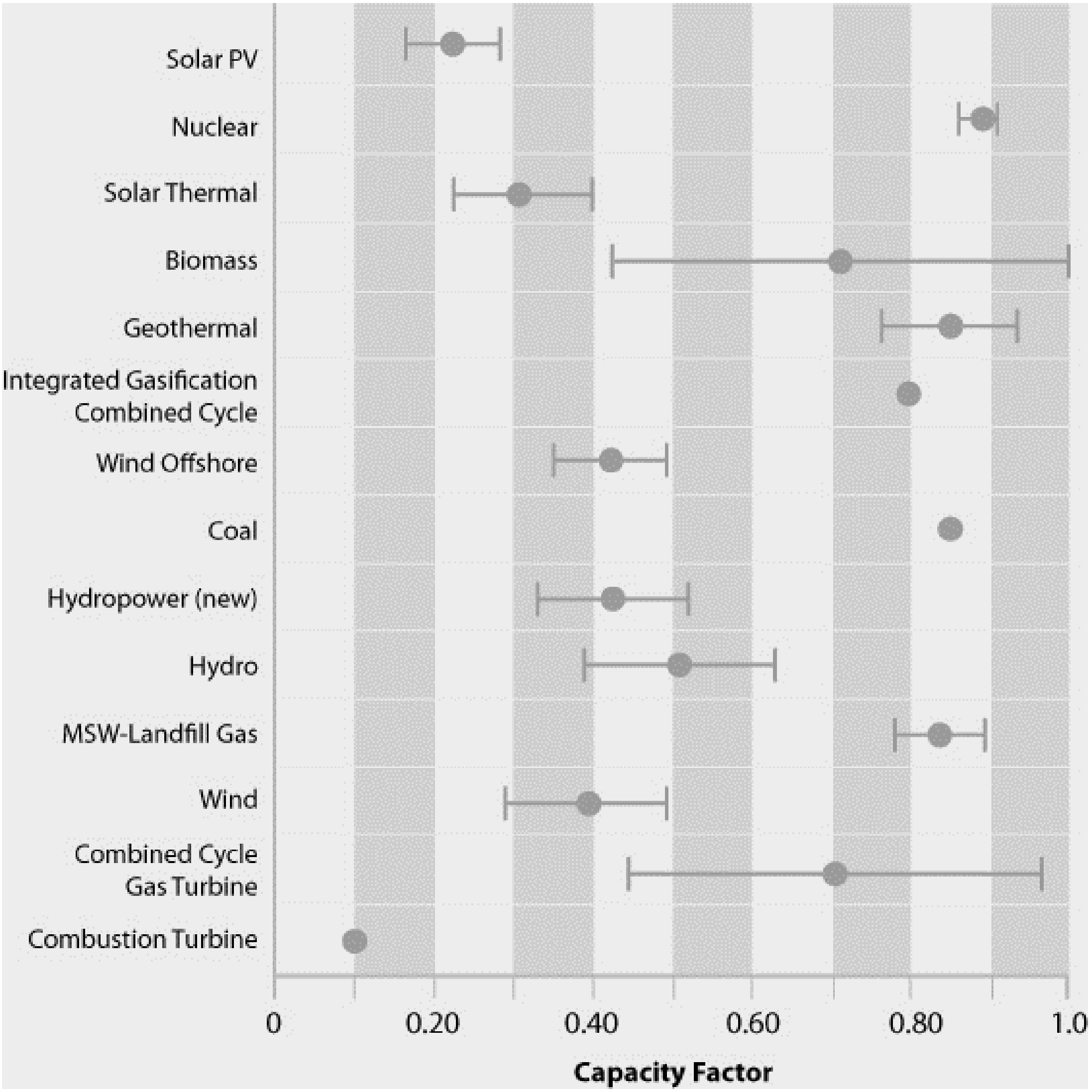
But, over a year-long period, both dams generate about the same amount of electricity because *seasonal variations in water availability on the Yangtze River in China limit power generation at Three Gorges Dam for a number of months during the year*.

Capacity Factor = 93.5 TWh / (197 TWh) = 0.47

- Three Gorges Dam, Yangtze River, China: 22,500 MW
  - Fully operational in 2012
  - Cost: $22.5 billion or 1 million $ / MW
  - Largest construction project in China since Great Wall
  - 1 million people displaced
  - Now provides ~1.7% of China's electricity needs

Source: http://en.wikipedia.org/wiki/Three_Gorges_Dam

Capacity Factor, Various Energy Sources

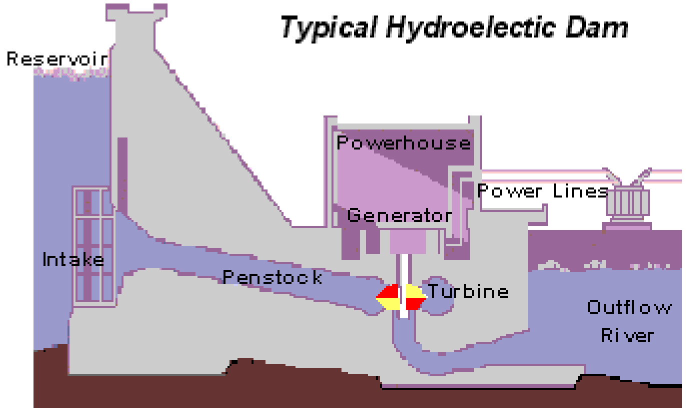


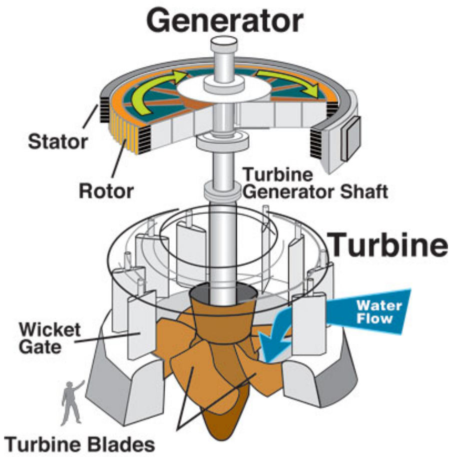
http://www.nrel.gov/analysis/tech_cap_factor.html

Hydro

Environmental Ledger

- Positive:
  - No NO_x and SO_x during operation
  - CO_2 release only during construction (page 90, Olah et al.)





http://ga.water.usgs.gov/edu/hyhowworks.html

- Negative:
  - Flooding: **over 1 million people displaced by Three Gorge Dam**
  - Soil fertility: High Aswan Dam in Egypt has resulted in fertile silt collecting at bottom of Lake Nassar, necessitating use of 1×10^6 tons of fertilizer
  - GHG emissions from lost forest and decaying biomass under dammed water

    http://www.springerlink.com/content/k30639u4n8pl5266/

    http://www.newscientist.com/article.ns?id=dn7046

Hydro

GREENHOUSE GAS EMISSIONS FROM A HYDROELECTRIC RESERVOIR (BRAZIL'S TUCURUí DAM) AND THE ENERGY POLICY IMPLICATIONS

PHILIP M. FEARNSIDE
Department of Ecology, National Institute for Research in the Amazon (INPA), Av. André Araújo, 2936, C.P. 478, 69011-970 Manaus, Amazonas, Brazil

Brazil as a whole emitted 53×10^6 t of carbon annually from fossil fuels in 1990 (La Rovere, 1996). The 7.0–10.1 $\times 10^6$ t emission of CO_2-equivalent C from Tucuruí in 1990 therefore represents 13–19% of the fossil fuel emission from the entire 170 million Brazilian population. The Tucuruí emission is 1.3–1.9 times that of the fossil fuel burned by the 17 million population of Brazil's largest city, São Paulo (10% of Brazil's population).

The above-water wood that produced 25–36% of the emission from Tucuruí in 1990 will eventually disappear. The methane emission that makes up the remainder of the dam's global-warming impact will decline to a lower plateau, but a poorly quantified part of this will continue as a permanent source. A São Paulo-sized emis-

Water, Air, and Soil Pollution 133: 69–96, 2002.

- Negative:
  - Flooding: over 1 million people displaced by Three Gorge Dam
  - Soil fertility: High Aswan Dam in Egypt has resulted in fertile silt collecting at bottom of Lake Nassar, necessitating use of 1×10^6 tons of fertilizer
  - **GHG emissions from lost forest and decaying biomass under dammed water**

    http://www.springerlink.com/content/k30639u4n8pl5266/

    http://www.newscientist.com/article.ns?id=dn7046

Top Hydropower Producing States, 2013

- Over half of the total U.S. hydroelectric capacity for electricity generation concentrated in three States (Washington, Oregon, and California)
- ~30% in Washington, location of the largest hydroelectric facility: Grand Coulee Dam.

http://www.eia.doe.gov/kids/energy.cfm?page=hydropower_home-basics-k.cfm

Wind

- Fastest growing renewable resource: 30% per year from 1992 to 2007

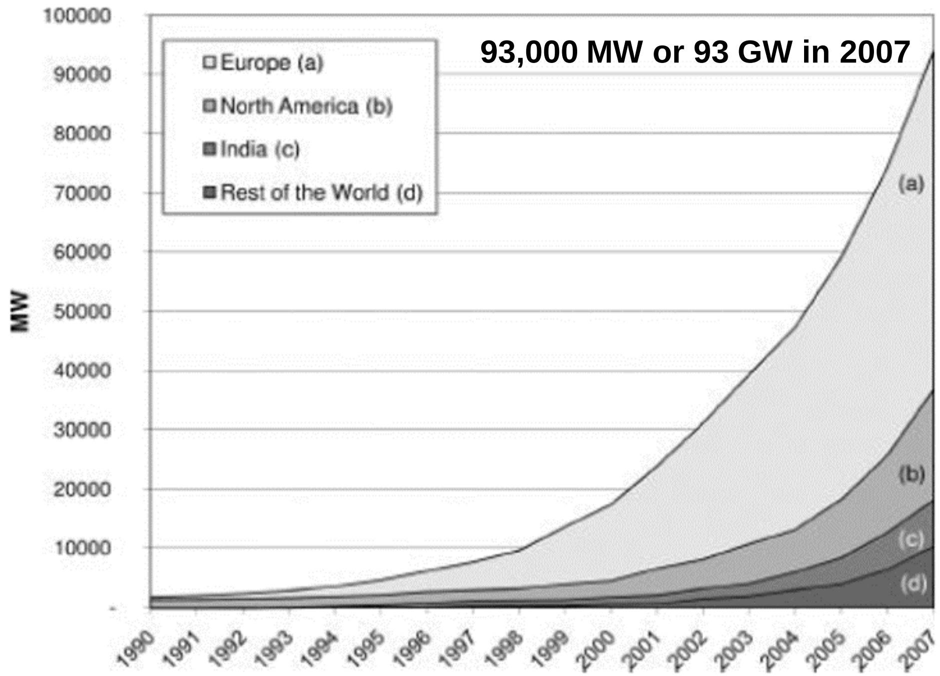


Figure 8.8 World wind power installed capacity. (Source: Global Wind Energy Council, European Wind Energy Association, IEA.)

Total Source	GW (year 2017)
Coal	1,928
Natural Gas	1,589
Hydro-electric	1114
Wind	**460**
Liquid Fossil Fuel	402
Nuclear	386
Solar	247
Other Renewable (Biomass)	142
Geothermal	17
Total	6285

- Germany: 44,470 MW capacity, generating 13.3% of country's electricity in 2015
  - Europe dominates wind energy turbine market
- Turbine capability has increased dramatically past 20 years:
  - Went from 20 m diameter generating 20-60 kW to 100 m diameter generating 2 MW

About 7.3% of world electricity production capacity right now

Wind Power Potential, World

- Wind power varies as [Wind Velocity]^3 :
  - Betz law: http://en.wikipedia.org/wiki/Betz%27_law
  - Installation benefits from accurate knowledge of wind fields

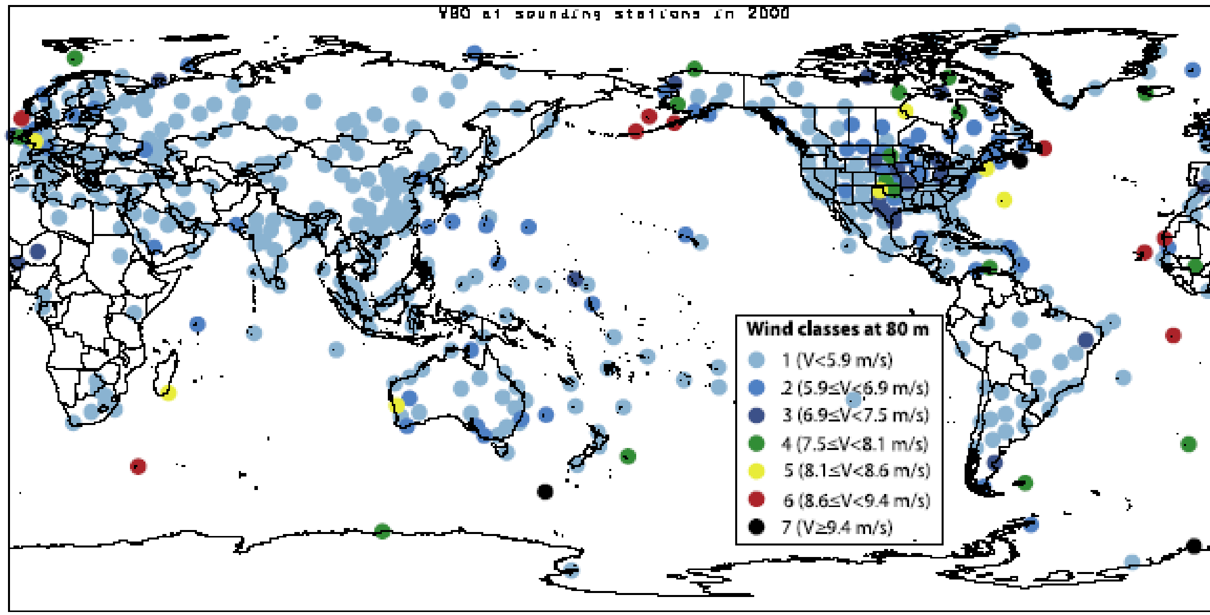


Figure 2. Map of wind speed extrapolated to 80 m and averaged over all days of the year 2000 at sounding locations with 20 or more valid readings for the year 2000.

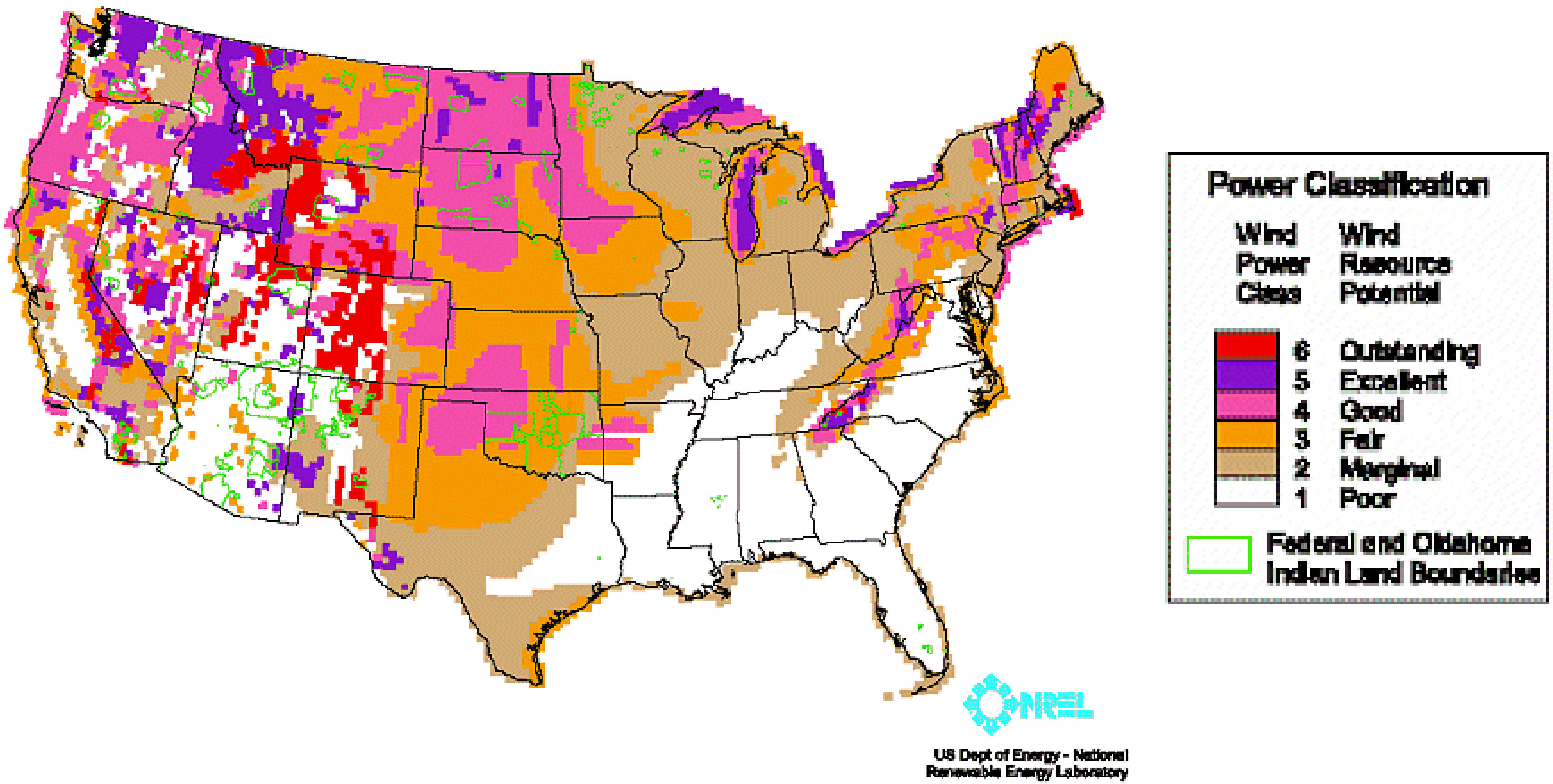
Archer and Jacobson, *JGR*, 2006

- Potential electricity generation from "sustainable Class 3 winds" is 72 Terawatts!
- Installation of ~5 Terawatts (current global electricity capacity) requires harnessing only a fraction of this potential with current turbine technology

Wind

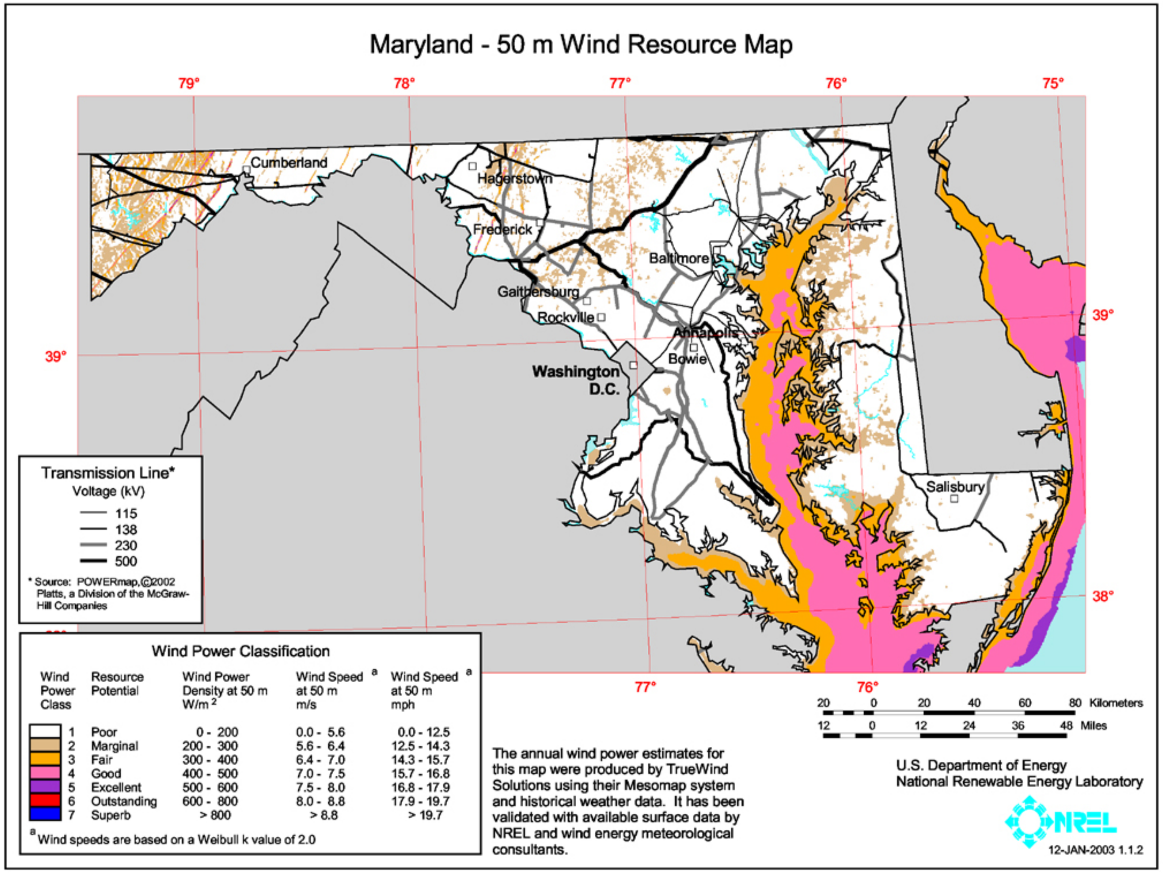
- Wind power varies as [Wind Velocity]^3 :
  - Betz law: http://en.wikipedia.org/wiki/Betz%27_law
  - Installation benefits from accurate knowledge of wind fields

Figure 13. Wind Resource Potential



http://www.eia.gov/cneaf/solar.renewables/ilands/fig13.html

Wind Power Potential, Maryland



http://www.eere.energy.gov/windandhydro/windpoweringamerica/images/windmaps/md_50m_800.jpg

Wind Power, Pros & Cons

Environmental Ledger

- Positive:
  - No emissions
  - Land on wind farm can be used for agriculture or livestock

- Negative:
  - Lightning strikes, turbine break / failure, or leaking fluid can lead to fire
  - Long-term performance of turbines not well established
  - Public resistance to visual impact or noise:

    June 29, 2003 - After a wind project was proposed several miles off the coast of Cape Cod, some environmentalists raised objections, as did U.S. Senator Ted Kennedy who owns a summer home in the area

    http://www.cbsnews.com/stories/2003/06/26/sunday/main560595.shtml

Geothermal

- US largest producer of geothermal electricity (absolute amount):

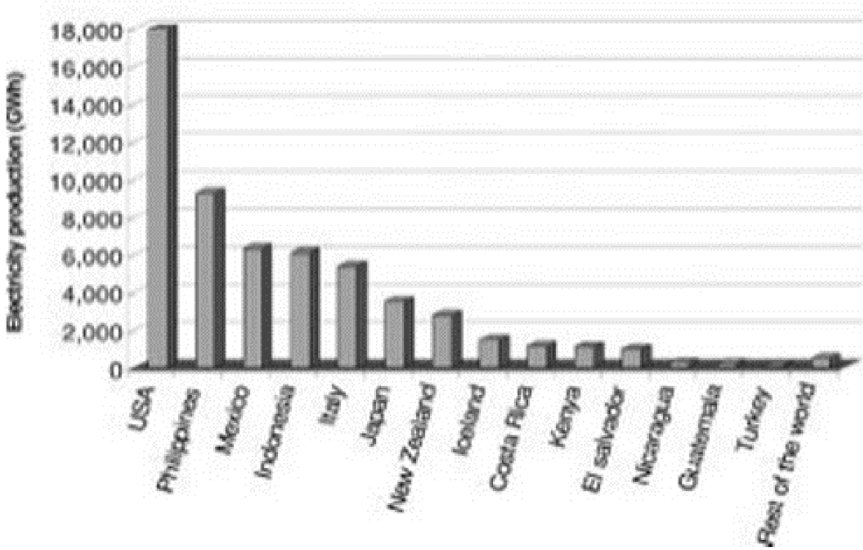


Figure 8.5 Geothermal electricity production, 2005. (Source: Bertani, R. [103].)

- El Salvador derives largest percentage of electricity from geothermal:

	Percentage of geothermy in the country's total electricity generation
El salvador	22
Kenya	19.2
Philippines	19.1
Iceland	17.2
Costa Rica	15
Nicaragua	9.8
New Zealand	7.1
Indonesia	6.7
Mexico	3.1
Guatemala	3
Italy	1.9
USA	0.5
Japan	0.3
Turkey	0.1
World	**0.3**

Olah *et al.*, *Beyond Oil and Gas: The Methanol Economy*, 2009.

Geothermal

• Geothermal electricity growing rapidly:

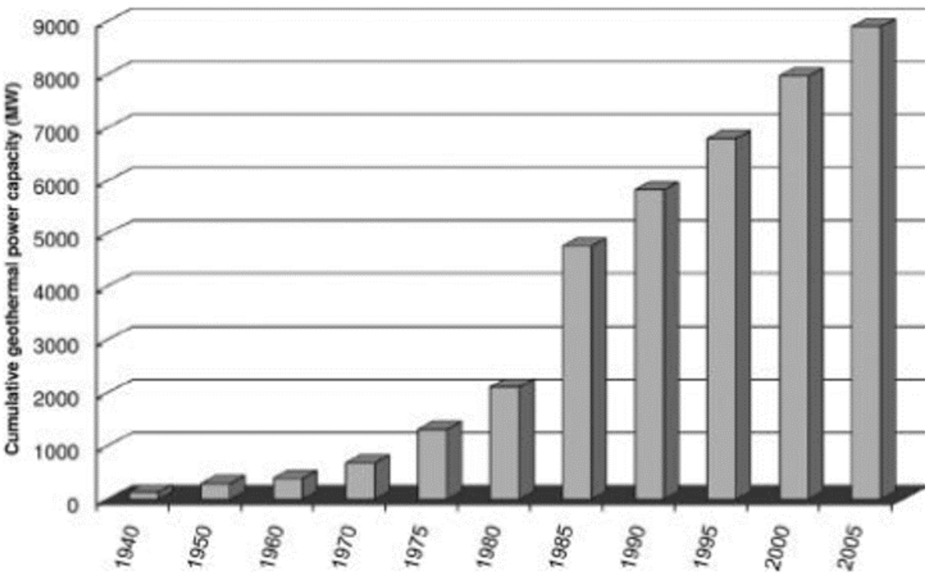


Figure 8.6 Worldwide development of geothermal electric power.

Total Source	GW (year 2017)
Coal	1,928
Natural Gas	1,589
Hydro-electric	1114
Wind	460
Liquid Fossil Fuel	402
Nuclear	386
Solar	247
Other Renewable (Biomass)	142
Geothermal	**17**
Total	6285

but total production capacity, about **17 GW (or 17,000 MW) in 2012**, represents only 0.3% of total world *electricity* generation capacity.

Olah *et al.*, *Beyond Oil and Gas: The Methanol Economy*, 2009.

Geothermal

- Temperature of source critical:
  - dry steam (T > 220°C) most profitable
  - hot water (150 to 300°C) can generate electricity using "flash steam" (depressurization and boiling)
  - low temperature (T < 150°C) used for heat (Iceland) or to extract H_2 from H_2O or fossil fuels

Where will favorable conditions for geothermal most likely be found?

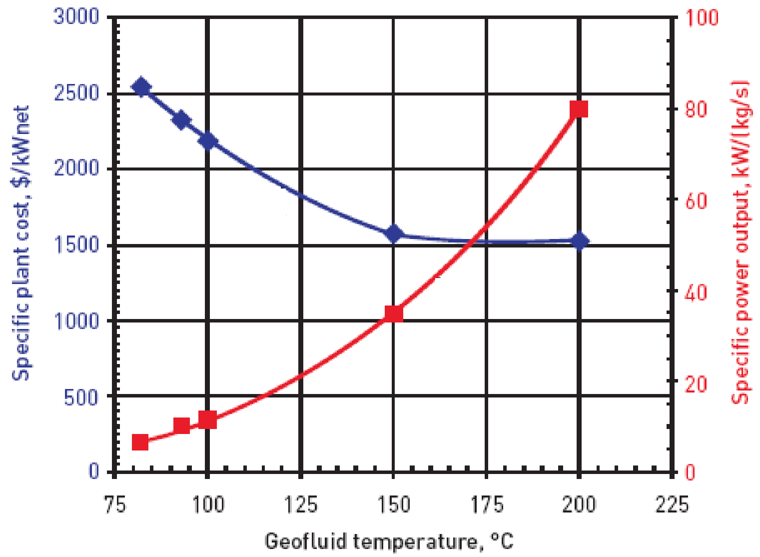
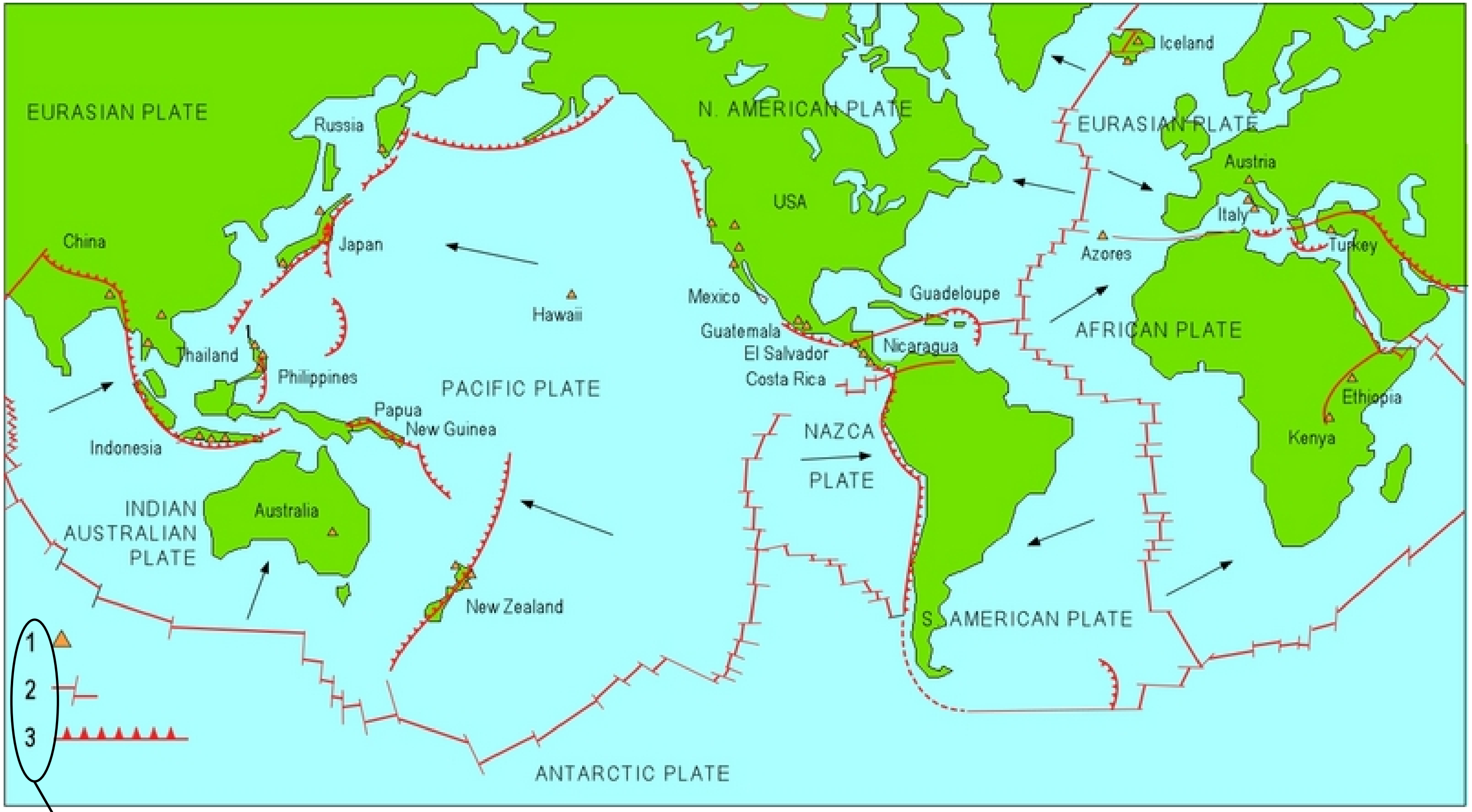


Figure 7.4 Cost and performance of 1 MW binary power plants as a function of geofluid temperature in degrees Celsius (°C).

http://geothermal.inel.gov/publications/future_of_geothermal_energy.pdf

Geothermal

- **Margins of tectonic plates most favorable**



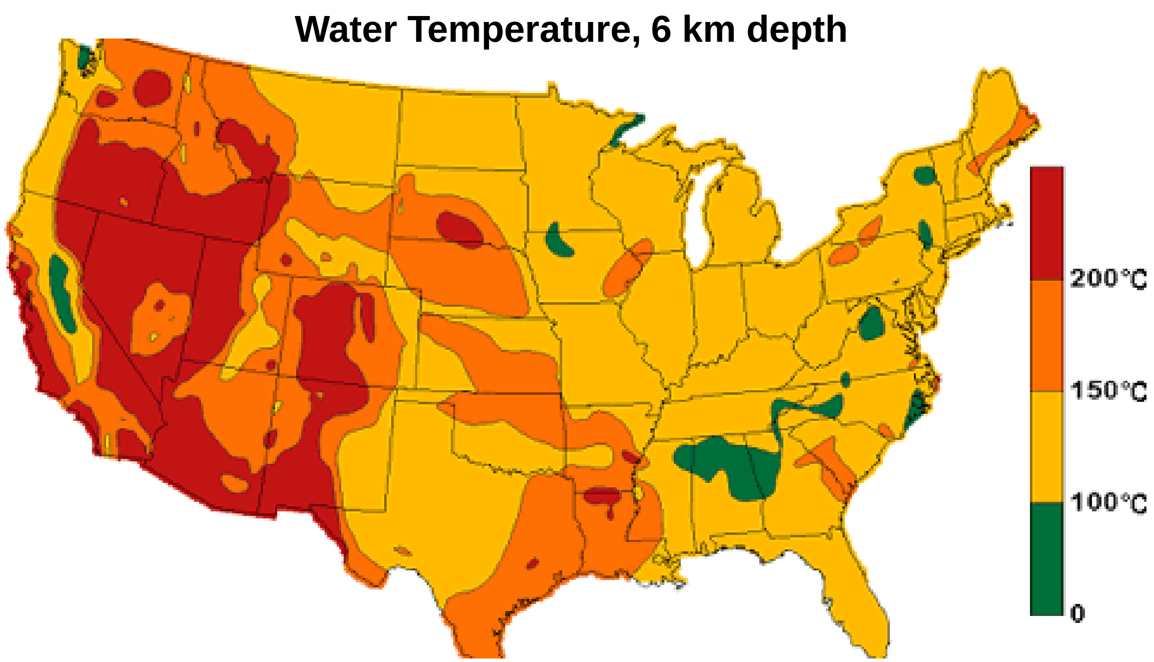
http://iga.igg.cnr.it/geo/geoenergy.php

(1) Geothermal fields producing electricity
(2) mid-oceanic ridges crossed by transform faults (long transversal fractures)
(3) subduction zones, where the subducting plate bends downwards and melts in the asthenosphere (~100 to 200 km below surface)

Geothermal

- Temperature of source critical:
  - dry steam (T > 220°C) most profitable
  - hot water (150 to 300°C) can generate electricity using "flash steam" (depressurization and boiling)
  - low temperature (T < 150°C) used for heat (Iceland) or to extract H_2 from H_2O or fossil fuels

Map of U.S. Water Temperature



http://www1.eere.energy.gov/geothermal/geomap.html

Geothermal

- Everything you ever wanted to know about Geothermal electricity: http://geothermal.inel.gov/publications/future_of_geothermal_energy.pdf
- Claim: geothermal is a largely untapped resource for electricity in the US
  - improvements in deep drilling and management of water flow within wells needed
- Strong association of electricity production and price:

GETEM: Geothermal Electric Technology Evaluation Model
EGS: Enhanced Geothermal Systems: i.e., engineered reservoirs that have been created to extract economical amounts of heat from geothermal resources

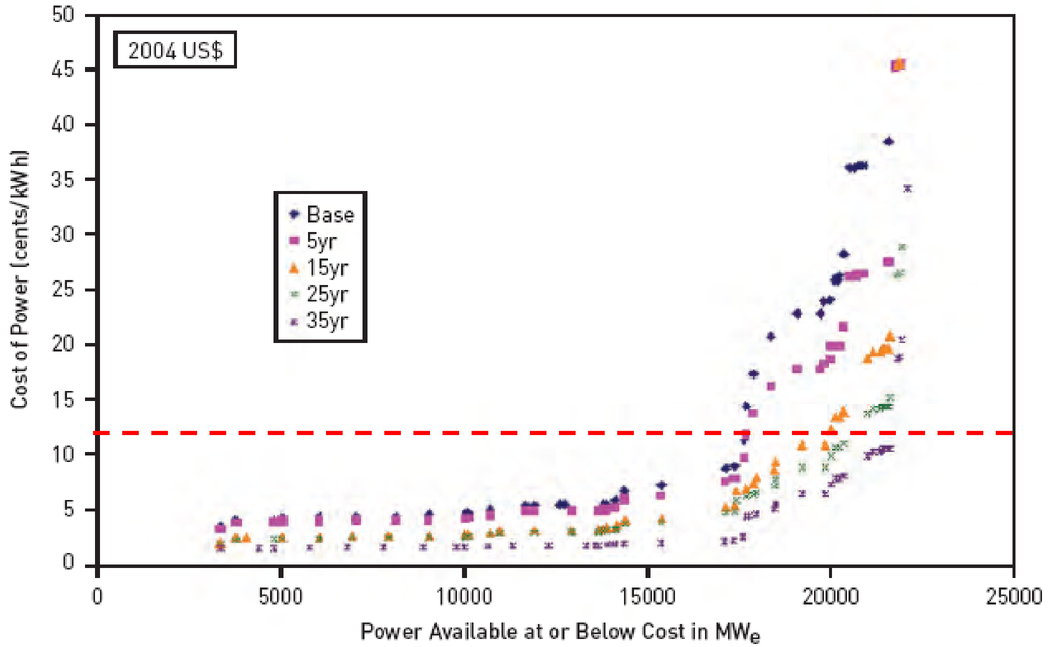


Figure 9.8 Predicted supply curves using the GETEM model for identified EGS sites associated with hydrothermal resources at depths shallower than 3 km. The base case corresponds to today's technology and the 5-, 15-, 25-, and 35-year values correspond to the state of technology at that number of years into the future.

Solar PV

- Sun delivers about 10,000 times more energy than world consumption
- Photovoltaic: converts solar energy into electricity
  - photovoltaic effect: Nobel Prize in 1921 went to __________
  - solar cells developed in 1960s for military and satellites
  - crystals from silicon, cadmium, copper, arsenic, etc
  - efficiency increased from 15% in mid-1970s to ~25% today
- PV capacity increased 30% per year from 1997 to 2007:

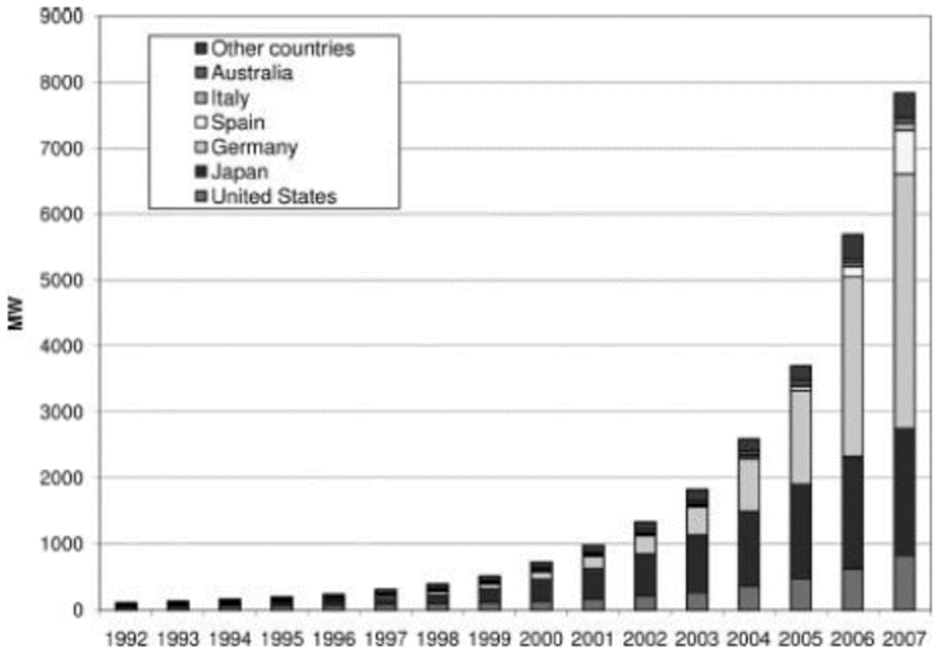
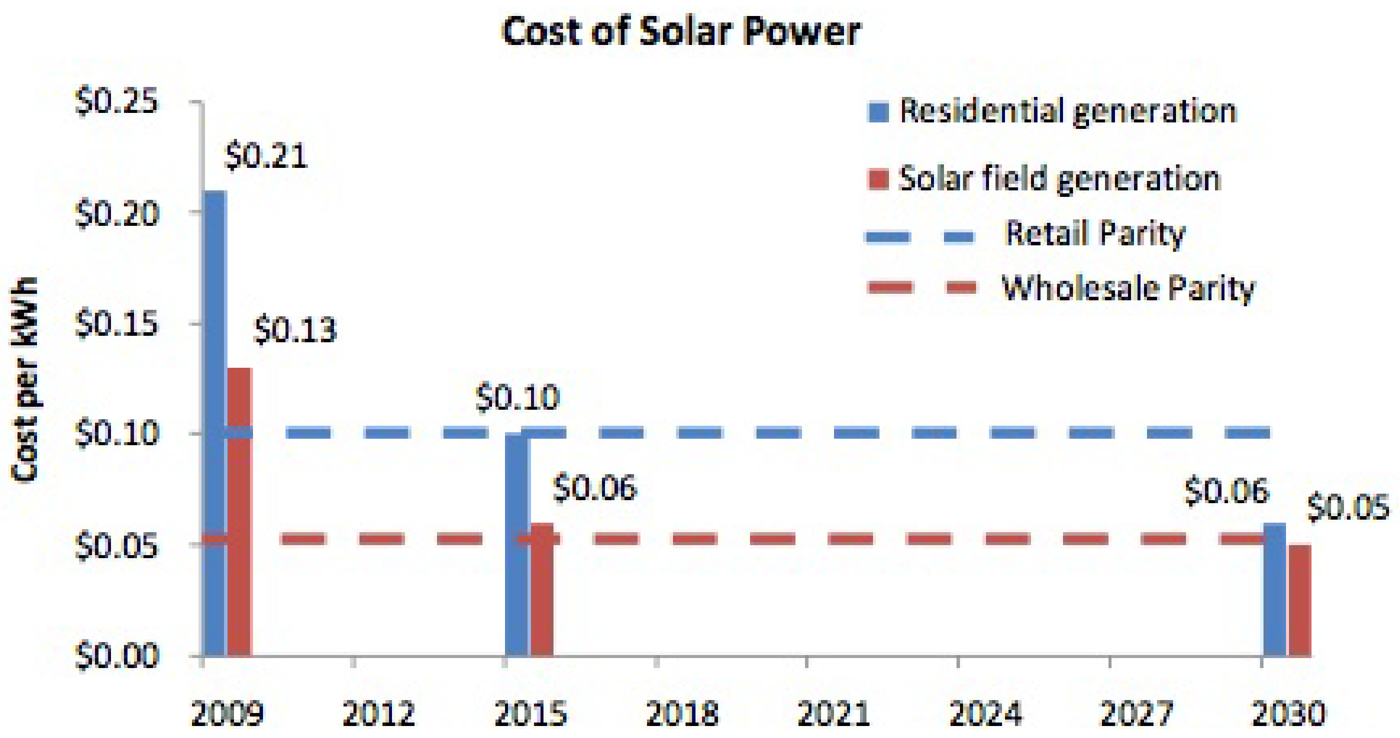


Figure 8.10 Cumulative installed photovoltaic (PV) power in reporting IEA countries. IEA-photovoltaic power systems programme.

Olah *et al.*, *Beyond Oil and Gas: The Methanol Economy*, 2009.

Solar PV Cost



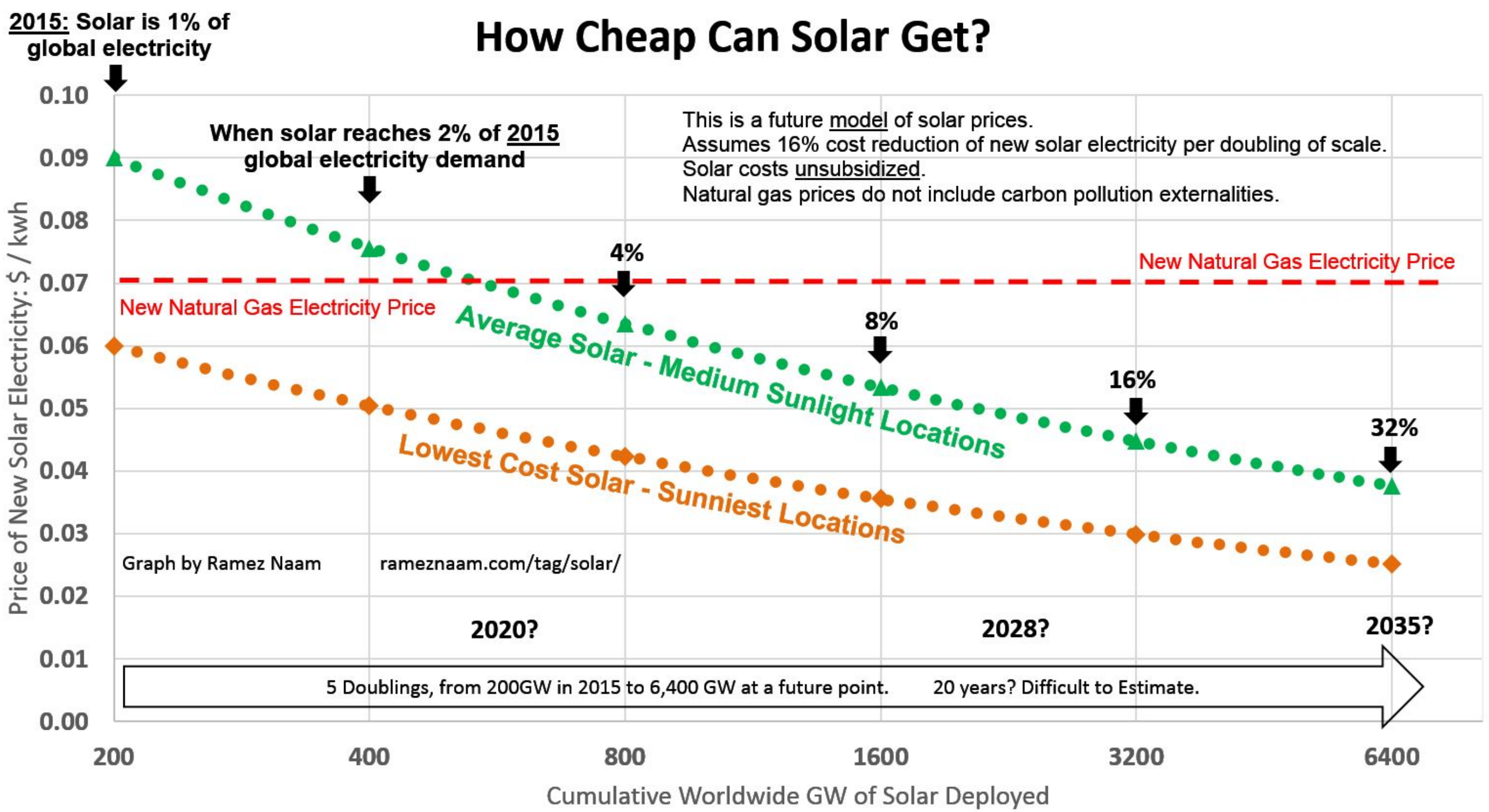
Graph shows the cost of solar PVs, representing total capital and operating costs over the lifetime of the panels, divided by the total electricity generated in kWh

Data from US DOE Solar Energy Technologies Program

https://energyonesolar.com/residential-rural-solar-energy/

Analysis shows production costs drop by ~16% for each doubling of capacity

Solar PV Cost



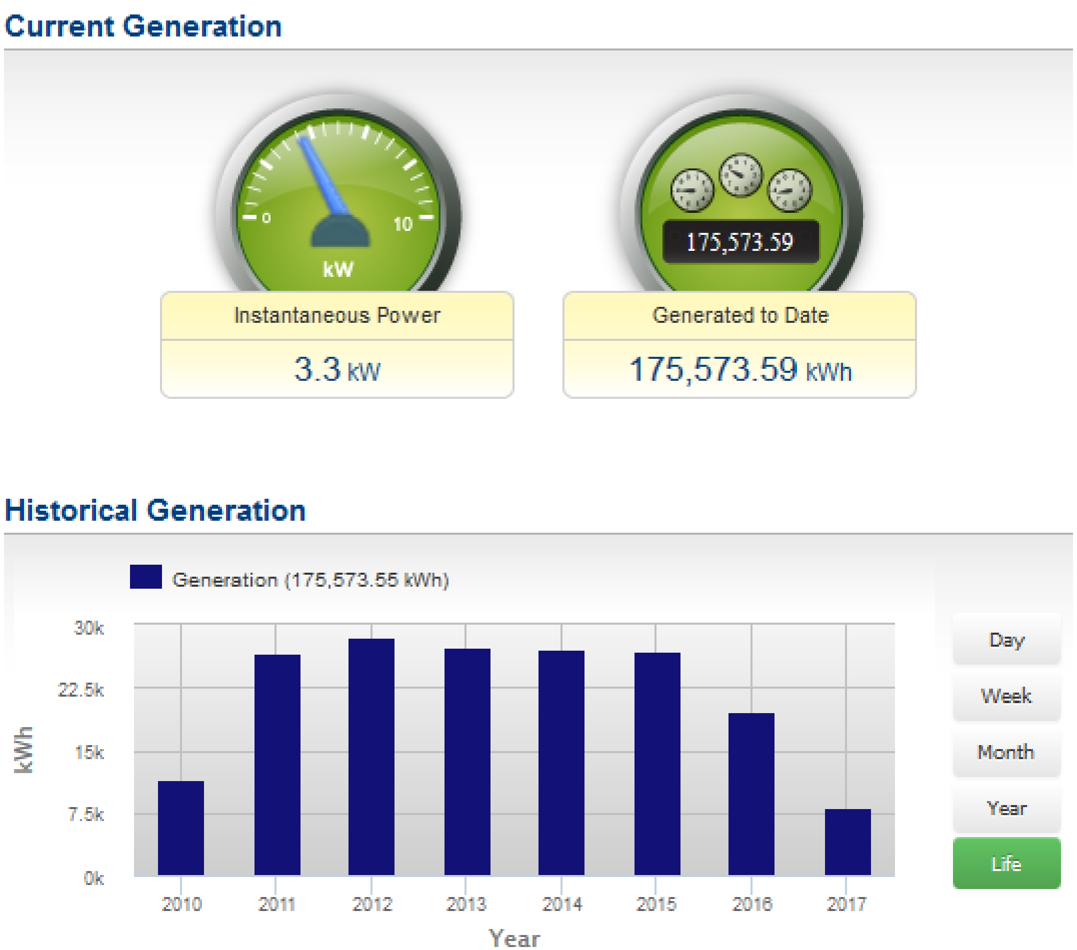
http://rameznaam.com/2015/08/10/how-cheap-can-solar-get-very-cheap-indeed/

Analysis based on production costs dropping by ~16% for each doubling of capacity

Route 1 (south of campus), just south of the new Whole Foods
22.7 kW system (**power**) has generated 175,574 kW-hours (**energy**) since 22 July 2010

http://www.universityparksolar.com & http://www.youtube.com/watch?v=khQsTJz2BkM

Solar PV Efficiency



Operational for:

- 2010: 205
- 2011: 365
- 2012: 366
- 2013: 365
- 2014: 365
- 2015: 365
- 2016: 366
- 2017: 115

Total: 2512 days

22.7 kW $\times$ 2512 days $\times$ 24 hrs/day=
 1.37 $\times$ 10^6 kW hr

Capacity Factor =
 1.76$\times$$10^5$ kW hr /1.37$\times$$10^6$ kW hr =

Financial return =
 1.76$\times$$10^5$ kW hr $\times$ 0.13 \$/kW hr =

http://peer1.datareadings.com/client/moduleSystem/Kiosk/site/bin/kiosk.cfm?k=elkWdi6e

64.8 kW $\times$ 1290 days $\times$ 24 hrs/day= 2.0 $\times$ 10^6 kW hr

Capacity Factor = 2.51×10^5 kW hr / 2×10^6 kW hr =

Financial return = 2.51 $\times10^5$ kW hr $\times$ 0.13 \$/kW hr =

Solar PV Efficiency

Material	Laboratory Efficiency	Production Efficiency
Monocrystalline Silicon	24 %	14 to 17 %
Polycrystalline Silicon	18 %	13 to 15%
Amorphous Silicon	13 %	5 to 7 %

Limited Efficiency

Limited spectral range of effective photons (depends on material used)

Surplus energy transformed into heat

Optical losses from shadowing and/or reflection

http://www.solarserver.com/knowledge/basic-knowledge/photovoltaics.html

Concentrated Solar Power (CSP)

- Parabolic mirrors heat fluid that drives Stirling engine
  - Fluid is permanently contained within the engine's hardware
  - Converts heat to energy
  - Theoretical efficiencies often challenging to achieve

    http://en.wikipedia.org/wiki/Stirling_engine
- Highest electrical efficiencies for solar → lowest costs!

  http://www.powerfromthesun.net/Book

  http://www.oilcrisis.com/us/ca/CaliforniaCSP_Benefits200604.pdf

Kramer Junction, Calif

Fully operational in 1991: 350 MW capacity

Low output in 1992 due to Pinatubo aerosol!

Present operating cost: ~11 ¢ / kWh

Nevada Solar One

Output: 64 MW capacity / 134,000 MW-hr / year

Could supply all US electricity needs
if built over a ~ 130 mile × 130 mile area

Construction cost: ~$2 / kW-hr for one yr's prod

Nevada Solar One

Project capacity: **64 MW** (power = energy / time)

Project output for 2012 to 2015: **118,000 MW-hr** (energy, or power × time)

Number of hours in year = 365x24 = 8760

Capacity Factor = 118,000 MW-hr / (64 MW × 8760 hr) =

Nevada Solar One

Output: 64 MW capacity

Could supply all US electricity needs
if built over a ~ 130 mile × 130 mile area

Construction cost: ~$2 / kW-hr for one yr's prod

Nevada Solar One's production is as follows (values in GW·h).[20]

Year	Solar	Fossil	Total
2007	41.21	0.38	41.59
2008	122.69	0.91	123.31
2009	120.65	2.43	123.07
2010	133.00	1.16	134.16
2011	128.26	1.99	130.26
2012	128.94	1.39	130.33
2013	112.79	2.31	115.10
2014	116.23	2.58	118.80
2015	105.65	2.14	107.79

http://en.wikipedia.org/wiki/Nevada_Solar_One#Production

Fossil backup, night time preservation, and morning pre-heating, is provided by natural gas and provides up to 2% of total output.

Nevada Solar One / US Energy Needs

US Electricity Consumption is 3913 TW-hr or 3913×10^6 MW-hr

Nevada Solar One output : 118,000 MW-hr

Nevada Solar One size = 0.6 square mile: (i.e., about 0.78 by 0.78 miles)

To meet US Energy Needs, would need 3913×10^6 MW-hr / 118,000 MW-hr or 3.3×10^4 more area

0.6 square mile $\times$ 3.3×10^4 = 2×10^4 square miles

[2×10^4 square miles]$^{1/2}$ = 141 by 141 miles

Cost: \$2 / KW-hr $\times$ 3913 TW-hr $\times$ (10^{12} W/TW) / (10^3 W/KW) = \$ 7.8×10^{12} or \$7.8 trillion dollars

US GDP in 2016 was \$18.6 trillion dollars