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

AOSC / CHEM 433 & CHEM 633

Ross Salawitch & Walt Tribett

Class Web Site: http://www.atmos.umd.edu/~rjs/class/spr2019

Next three lectures:

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

https://gigawattglobal.com/projects3/rwanda/

Lecture 19

25 April 2019

Energy and Power

Simple equation connects energy and power:

Energy = Power × Time

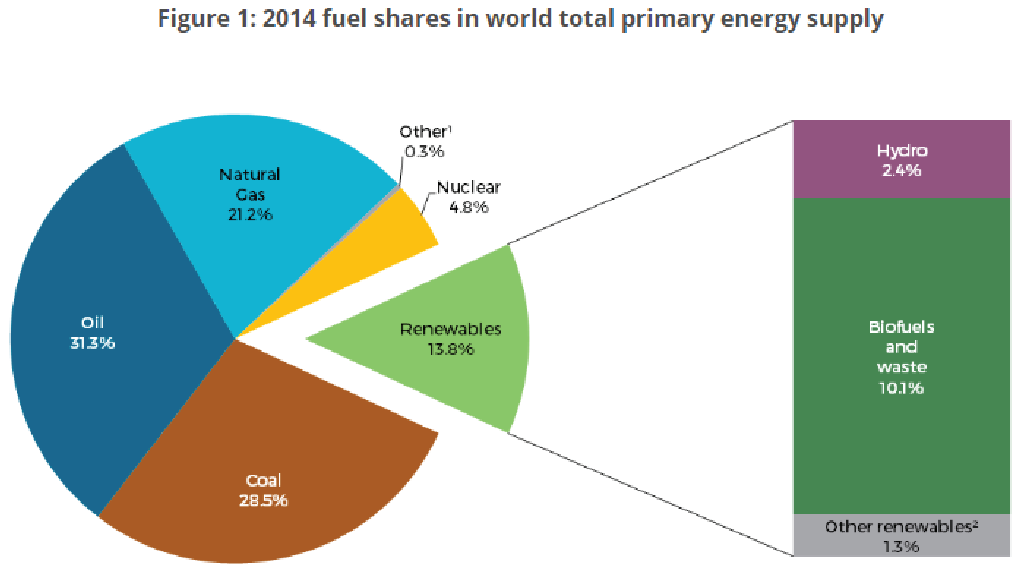
Size of a ***power*** plant is commonly measured in units of power:

- kW (kilo: 10^3 Watts): Home solar
- MW (mega: 10^6 Watts) Industrial
- GW (giga: 10^9 Watts): Massive Hydroelectric
- TW (terra: 10^{12} Watts): Large Nation and/or Global
- Most solar arrays are "sized" in terms of kW

Output of a **power** plant in units of ***energy***:

- kWh (kilo: 10^3 W hour)
- MWh (mega: 10^6 W hour)
- GWh (gig: 10^9 W hour)
- Output of most solar arrays are metered in terms of kWh

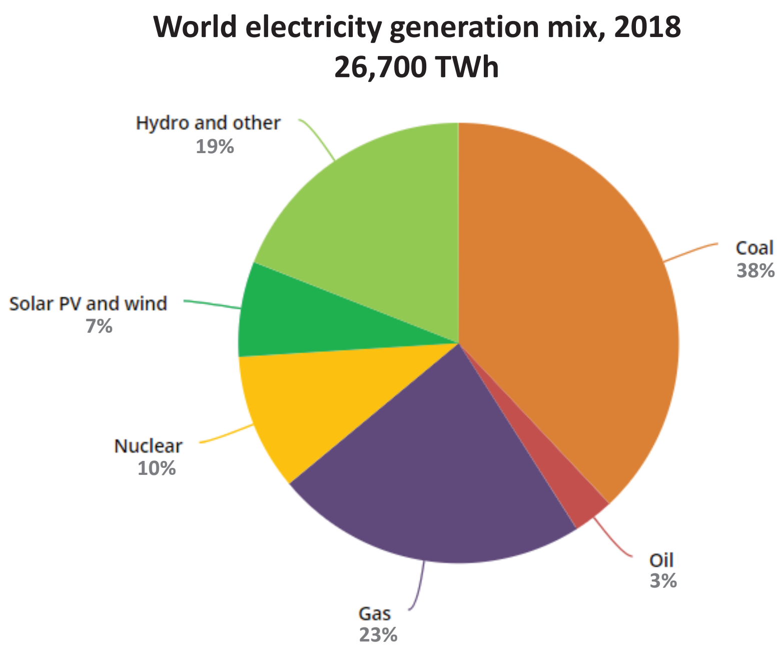
World Energy Supply: units of Energy



In 2014, world obtained
~80% of its **energy**
from combustion of fossil fuels

https://www.iea.org/newsroom/news/2016/july/renewable-energy-continuing-to-increase-market-share.html

World Electricity Update

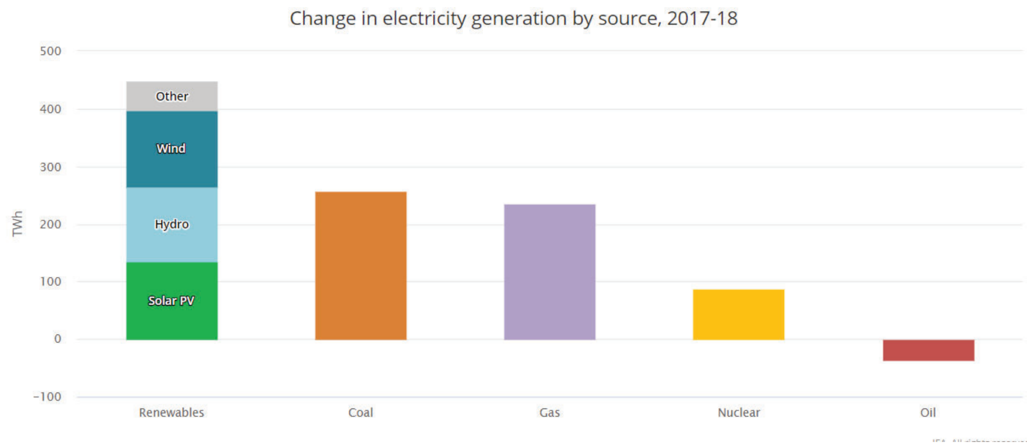


https://www.iea.org/geco/electricity/
See also: https://renewablesnow.com/news/renewables-supply-25-of-global-power-in-2017-iea-606070

Glass half empty (compare to slide 3):
In 2018, world still obtained ~64% of its **electricity** from combustion of fossil fuels

Glass half full (compare to slide 3):
In 2017, world obtained ~25% of its **electricity** from renewables,
compared to 18% in 2005.

World Electricity Trend



https://www.iea.org/geco/electricity/
See also: https://renewablesnow.com/news/renewables-supply-25-of-global-power-in-2017-iea-606070

Global electricity demand increased by 4% in 2018; fastest increase since 2010, when global economy recovered from the financial crisis.

China and U.S. accounted for 70% of global demand growth. In China, electricity demand increased by 8.5, led by the industrial sector, including iron, steel and other metals, cement and construction, as well as higher demand for cooling.

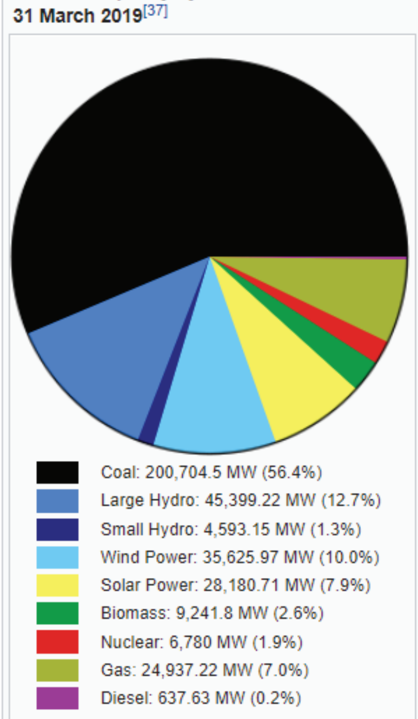
In the US demand jumped by nearly 4% to a record level of almost 4 000 TWh, 17% of the global total. Most of the growth was attributable to a hotter summer and a colder than average winter, which increased power demand in buildings.

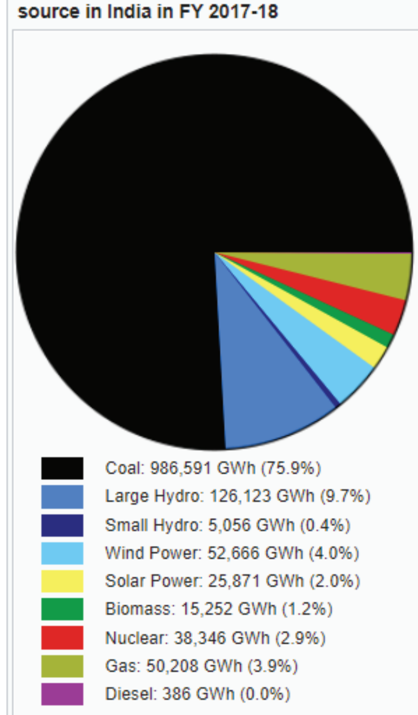
India's power demand increased by around 65 TWh, or 5.4%, a slower rate than the previous year.

The increase was driven by higher demand in buildings, especially coming from air conditioning, as well as higher access to electricity.

Last year, India completed the electrification of all its villages, with electricity connections extended to around 30 million people in the last 2 years.

Electricity Generation in India


Installed capacity by source in India as on 31 March 2019[37]


Electricity generation (utility sector) by source in India in FY 2017-18

https://en.wikipedia.org/wiki/Electricity_sector_in_India

World Installed ***Electricity*** Generating ***Capacity***:

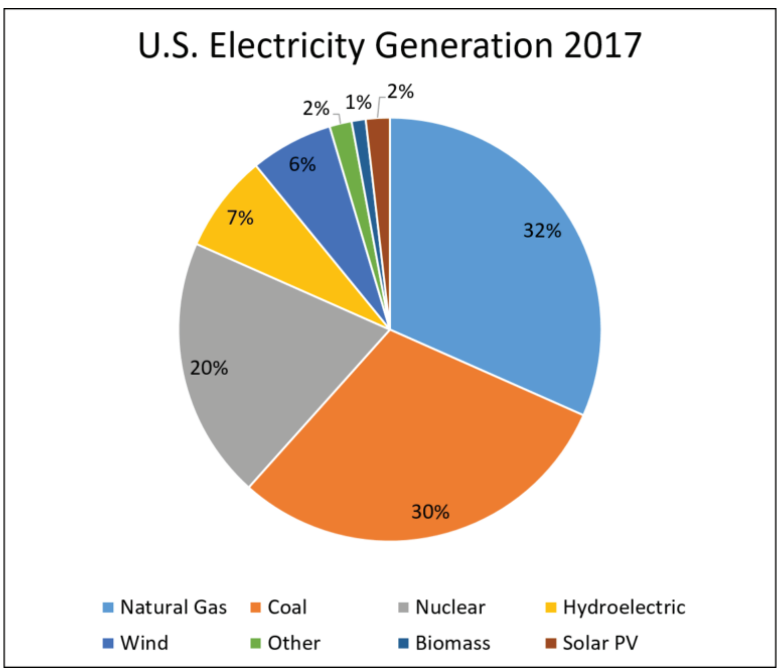
Power (Energy/Time)

Total Source	GW (year 2018)
Coal	2,167
Natural Gas	1,769
Hydro-electric	**1140**
Wind	**524**
Liquid Fossil Fuel	381
Nuclear	374
Solar	**352**
Other Renewable (Biomass)	290
Geothermal	**19**
Total	7016

Source: https://www.eia.gov/outlooks/archive/ieo17/ieo_tables.php

In 2018, **38.4%** of global electricity generating capacity does not release prodigious GHGs to the atmosphere (33.1% of this 38.4% involves hydro, wind, solar, biomass, and geothermal)

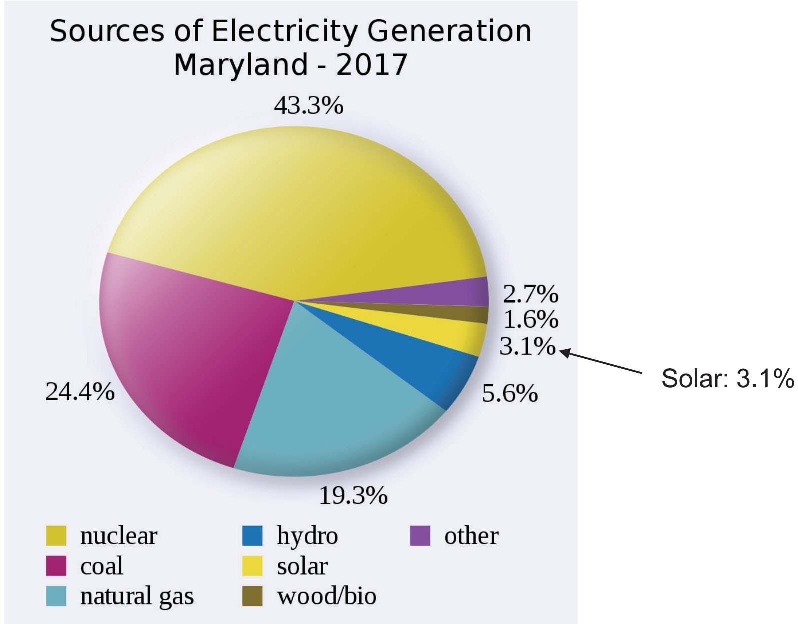
U.S. *Electricity* Supply: 2017



http://yourenergy.extension.colostate.edu/fuels-electric-grid/

In 2016, the U.S. obtained ~64% of its electricity from fossil fuels & ~16% from hydro, wind, biomass, and solar

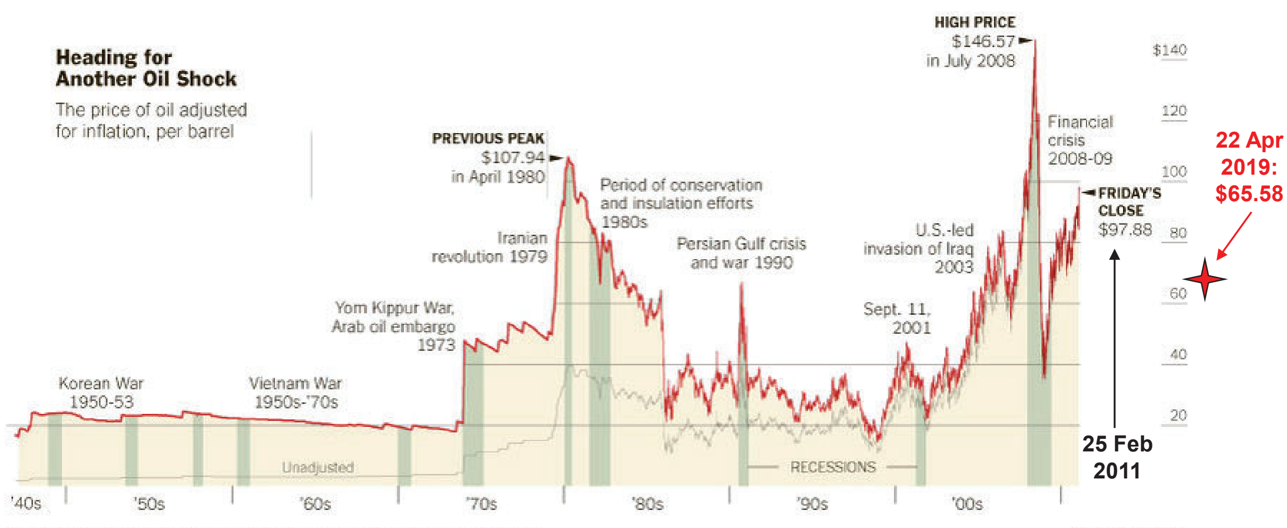
MD *Electricity* Supply: 2017



https://commons.wikimedia.org/wiki/Category:Charts_of_Electricity_Generation_Sources_-_U.S._State

In 2017, Maryland obtained ~44% of its electricity from fossil fuels & ~13% from hydro, wind, biomass, and solar

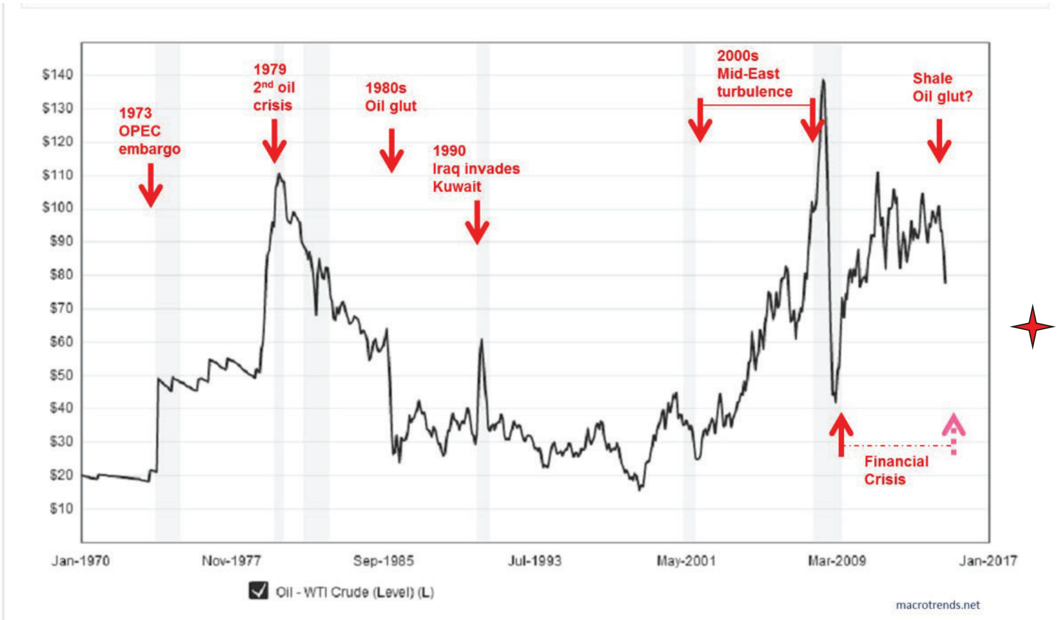
Market Force #1: Cost of Fossil Fuel



http://www.nytimes.com/2011/02/28/business/global/28oil.html

Graph shows cost of a barrel of oil

Market Force #1: Cost of Fossil Fuel



Crude Oil Price History Chart

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

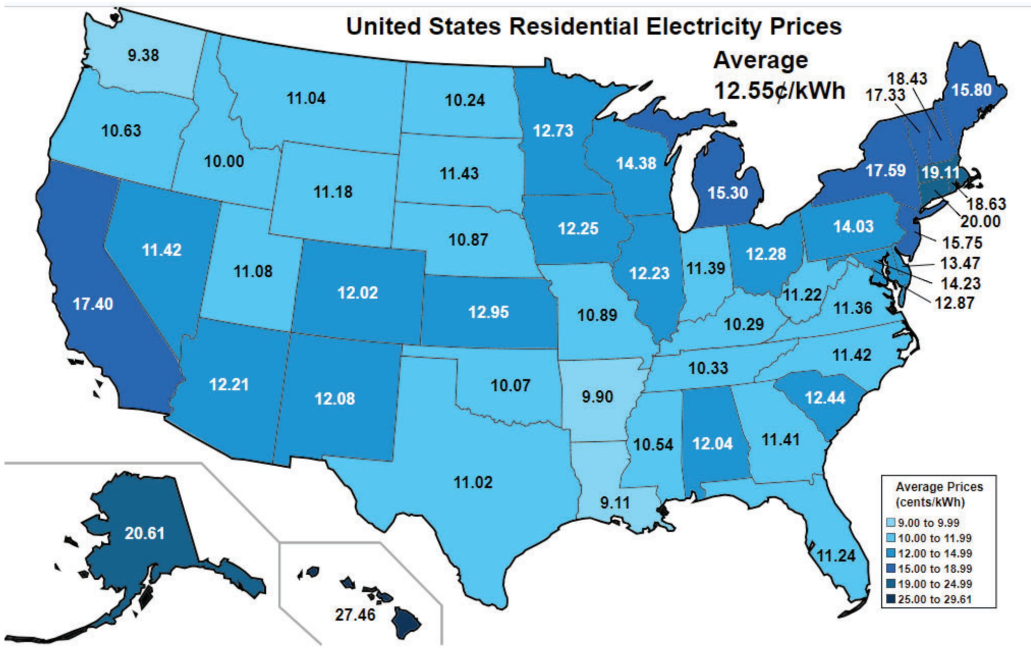
Graph shows cost of a barrel of oil

Market Force #1: Cost of Fossil Fuel

Graph shows cost of a barrel of oil

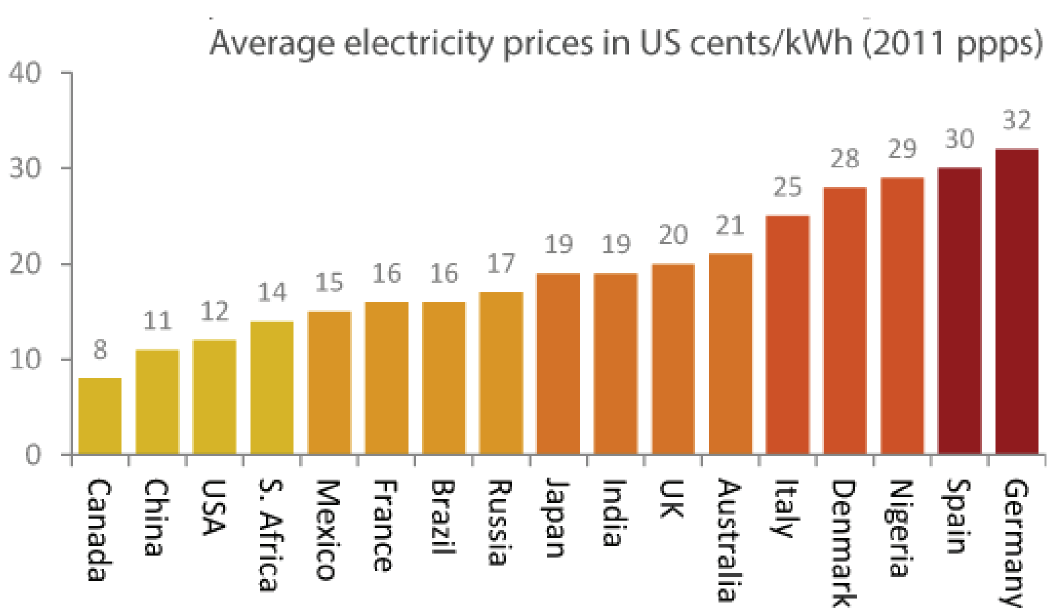
https://www.macrotrends.net/1369/crude-oil-price-history-chart

U.S average residential retail price of electricity: 12.55 cents per kilowatt-hour in 2016



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

Price of Electricity varies a lot Internationally

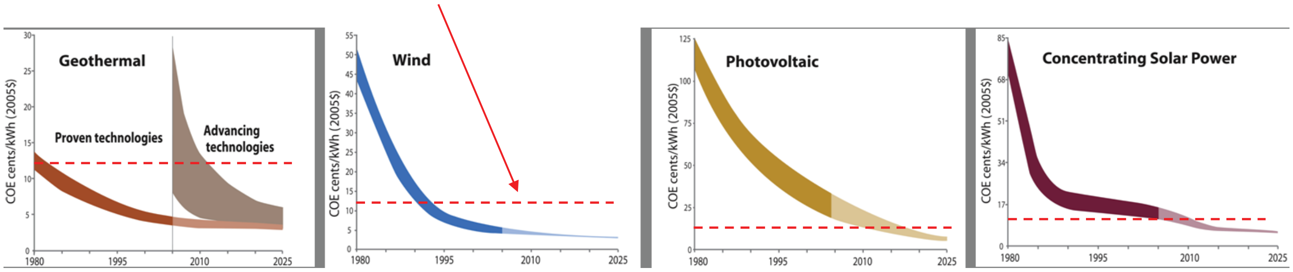


ppps: purchasing power parities

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

Market Force #2: Cost of Electricity from Renewables ↓

2016 US Average Cost of Electricity: ~12.55 cents per kw-hour



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

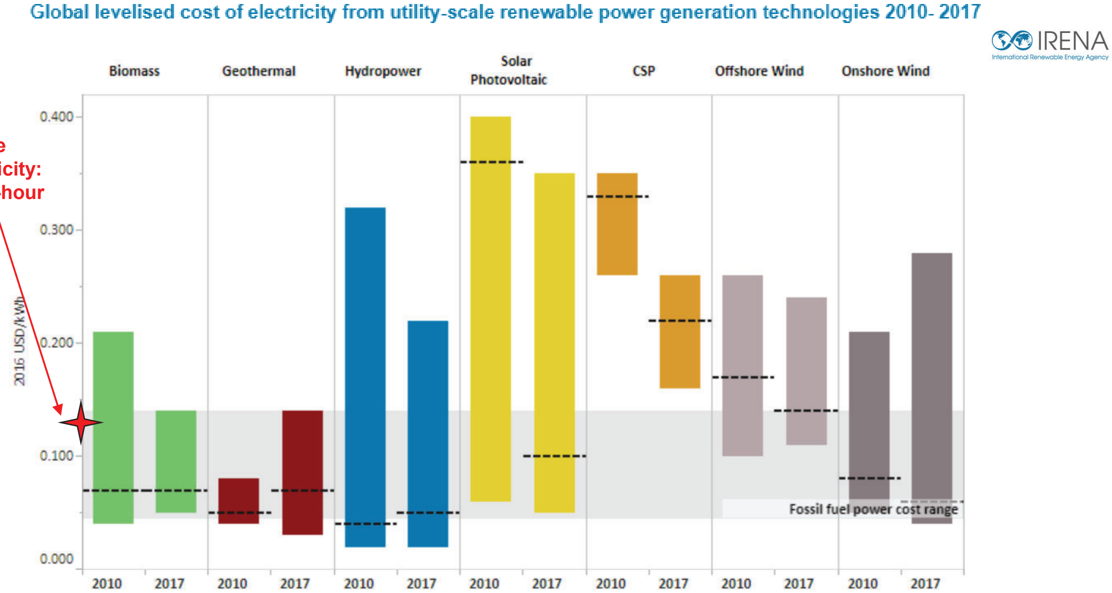
The notational view "back in the day" was the cost of generating electricity from renewables would drop due to innovation, and the cost of generating electricity from fossil fuels would rise due to scarcity.

Alas, abundant natural gas (methane, CH_4) from fracking (the f-word in climate) has stabilized if not lowered the cost of generating electricity from fossil fuels.

Market Force #2: Cost of Electricity from Renewables ↓

Global levelised cost of electricity from utility-scale renewable power generation technologies 2010- 2017

2016 US Average Retail Cost of Electricity: ~12.55 cents per kw-hour



Source: IRENA Renewable Energy Cost Database. **Note:** All costs are in 2016 USD. The dashed lines are the global weighted average LCOE value for plants commissioned in each year. Cost of Capital is 7.5% for OECD and China and 10% for Rest of World. The band represents the fossil fuel-fired power generation cost range.

http://resourceirena.irena.org/gateway/dashboard/?topic=3&subTopic=1065 © IRENA

Biomass, Geothermal, Hydro, Solar PVs, and Onshore Wind cost competitive with fossil fuels.
Utility-scale renewable options of Concentrated Solar and Offshore Wind still lag.

LCOE: Levelized Cost of Electricity https://en.wikipedia.org/wiki/Cost_of_electricity_by_source

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

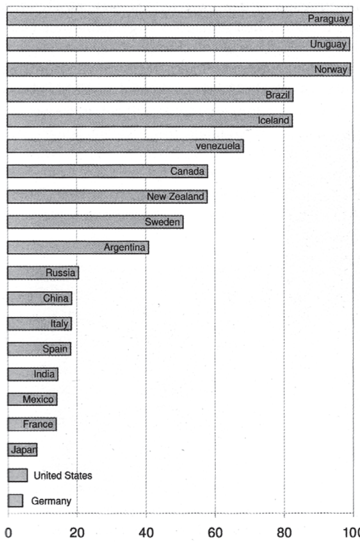


Figure 8.2 Percentage of electricity produced from hydropower in different countries. (Source: CIA World Factbook, December 2003.)

Hydro: 16 % of world electricity capacity

Total Source	GW (year 2018)
Coal	2,167
Natural Gas	1,769
Hydro-electric	**1140**
Wind	524
Liquid Fossil Fuel	381
Nuclear	374
Solar	352
Other Renewable (Biomass)	290
Geothermal	19
Total	7016

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	[58]
2009	26	79.470	[59]
2010	26	84.370	[60]
2011	29	78.290	[61]
2012	32	98.100	[62]
2013	32	83.270	[63]
2014	32	98.800	[64]
2015	32	87.000	[65]
2016	32	93.500	[66]
2017	32	97.600	[67]
2018	32	120.00	[68]

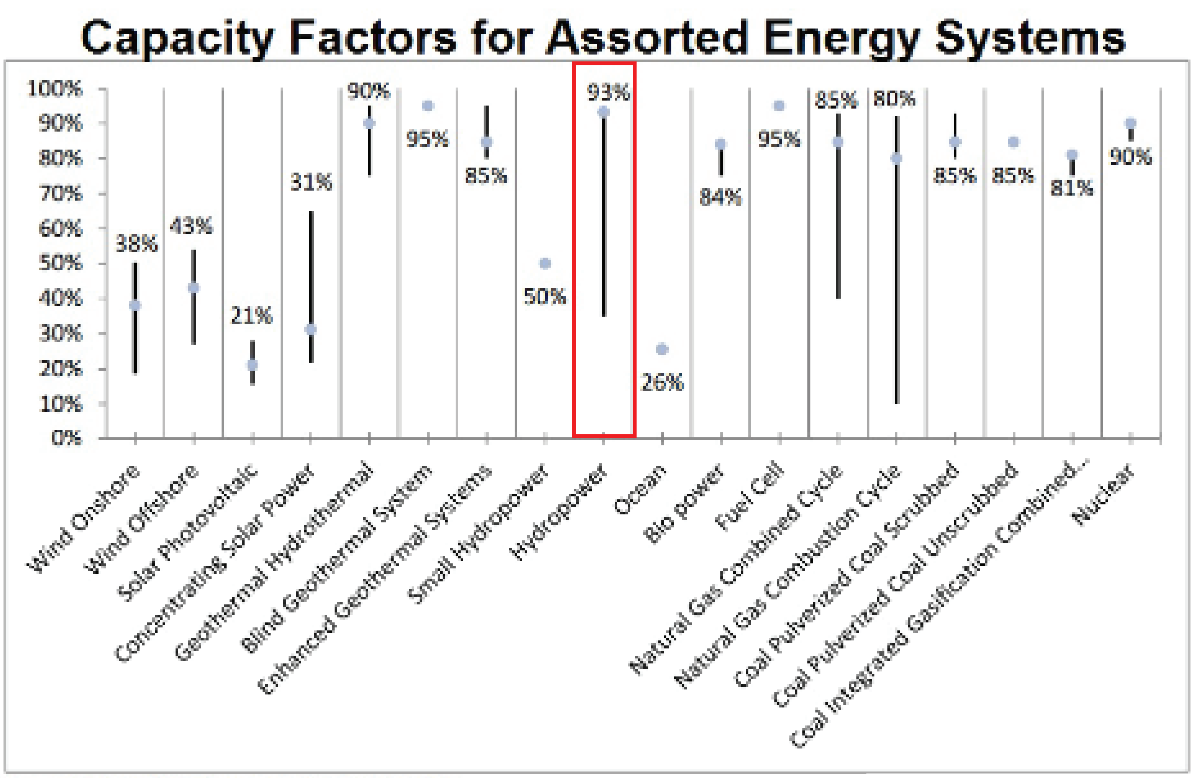
Size (power) of all 32 units is 22,500 MW

If Three Gorges had run at full capacity for 24/365:
$22{,}500 \text{ MW} \times 8760 \text{ hr} = 1.97 \times 10^8 \text{ MWh} =$
$1.97 \times 10^8 \text{ MWh} \times \text{TWh}/(10^6 \text{ MWh}) = 197 \text{ TWh}$

Capacity Factor =
TWh / (TWh) = 0.49

Mean output for years with all 32 units = 96.9 TWh

Sources: http://en.wikipedia.org/wiki/Three_Gorges_Dam
http://www.chinadaily.com.cn/a/201812/21/WS5c1c5eeca3107d4c3a002168.html



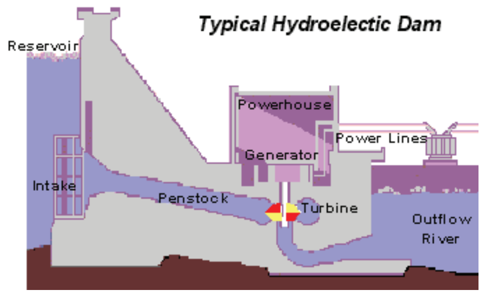
Source: DOE and NREL "Transparent Costs Database"
Note: Blue dots represent estimate for the average capacity factor of each technology.

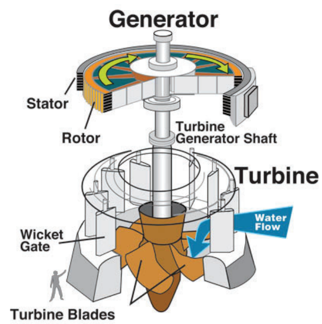
http://www.lightevolution.co.uk/blog/geothermal-visual-capacity-factors-for-assorted-energy-systems/

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 $1{\times}10^6$ 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 emission source may therefore be permanent. These impacts consider the 100-yr global warming potentials without discounting (currently used by the Kyoto Protocol); were discounting or other time-preference weighting mechanisms to be applied, the relative impact of hydroelectric dams could be higher than those calculated here by a factor of two or more (Fearnside, 1997a).

Water, Air, and Soil Pollution 133: 69–96, 2002.
© 2002 *Kluwer Academic Publishers. Printed in the Netherlands.*

GHG emissions from lost forest and decaying biomass under dammed water

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

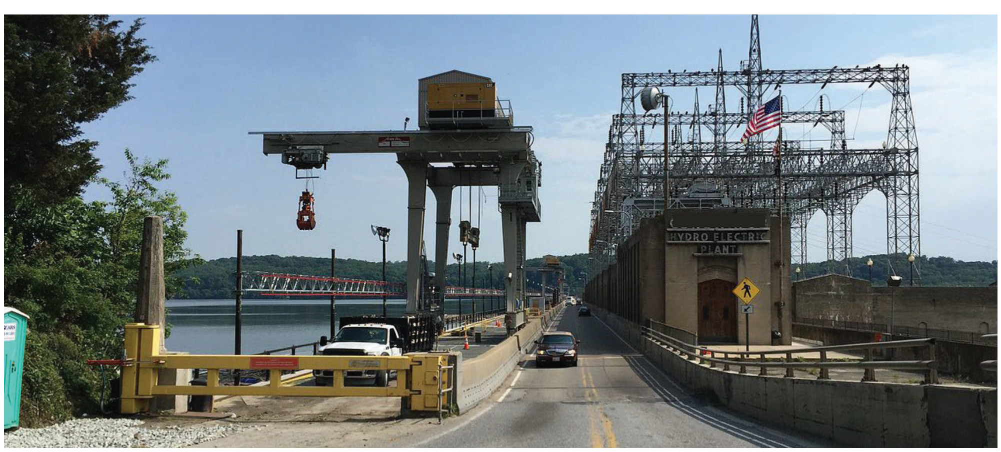
http://www.newscientist.com/article.ns?id=dn7046

Top Hydropower Producing States, 2018

- 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.

https://www.eia.gov/energyexplained/images/charts/hydropower-use-map-large.gif

Hydro in Maryland



Wind

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

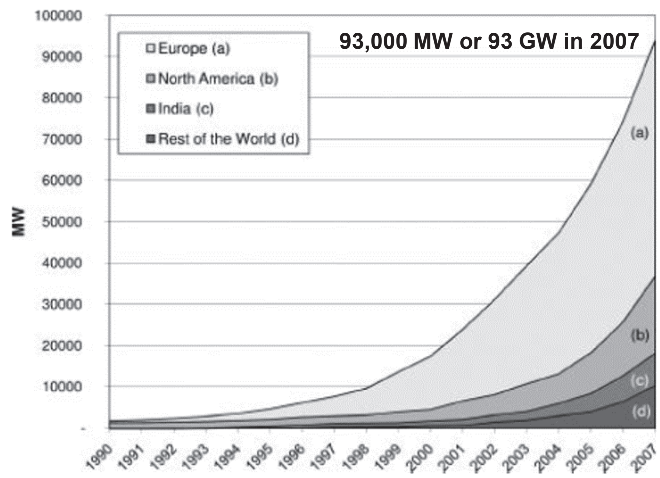


Figure 8.8 World wind power installed capacity. (Source: Global Wind Energy Council, European Wind Energy Association, IEA.)

Total Source	GW (year 2018)
Coal	2,167
Natural Gas	1,769
Hydro-electric	1140
Wind	**524**
Liquid Fossil Fuel	381
Nuclear	374
Solar	352
Other Renewable (Biomass)	290
Geothermal	19
Total	7016

- 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 7.5% 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

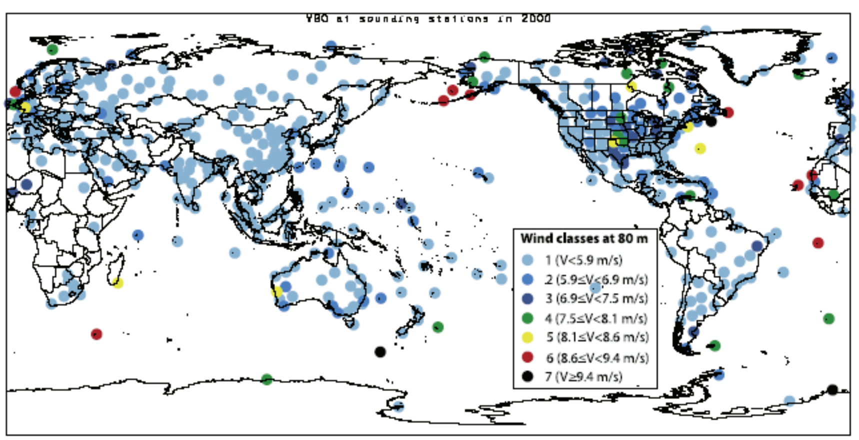


Figure 2. Map of wind speed extrapolated to 80 m and averaged over all days of the year 2000 at sounding locations with 20 or more valid readings for the year 2000.

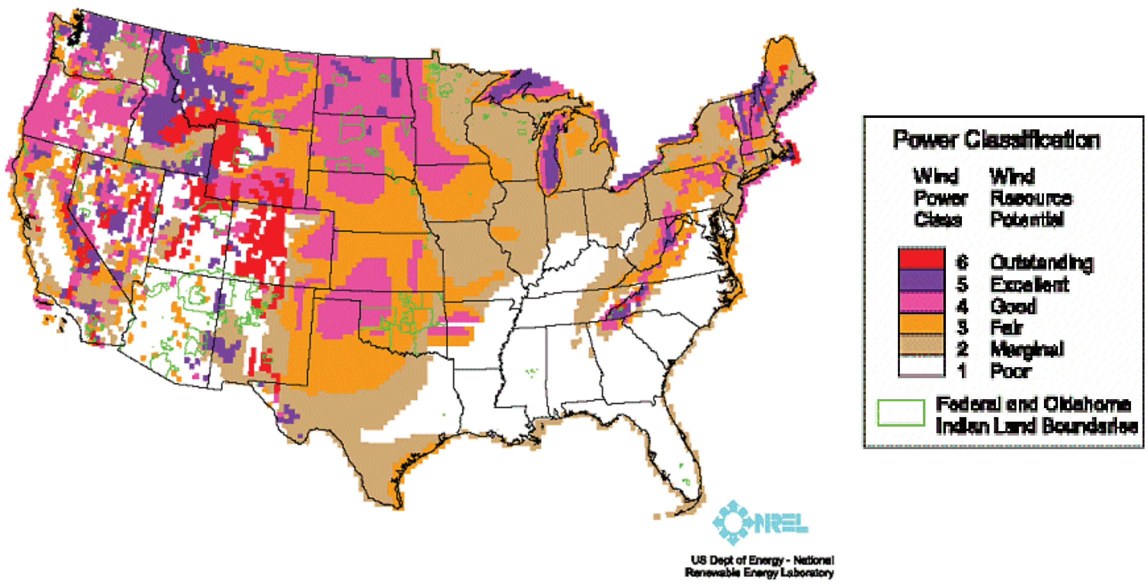
Archer and Jacobson, *JGR*, 2006

- 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

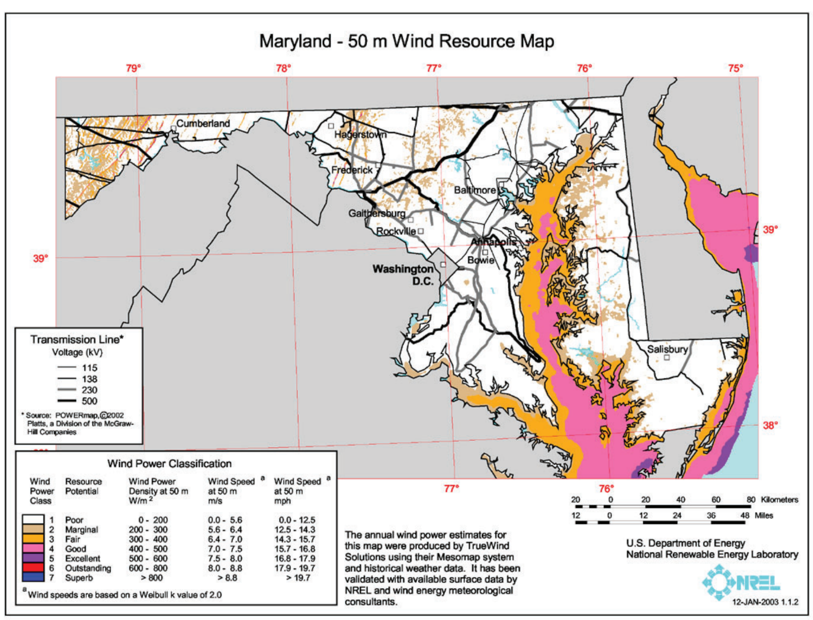
- Wind power varies as [Wind Velocity]^3 :
  - Betz law: http://en.wikipedia.org/wiki/Betz%27_law
  - Installation benefits from accurate knowledge of wind fields

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):

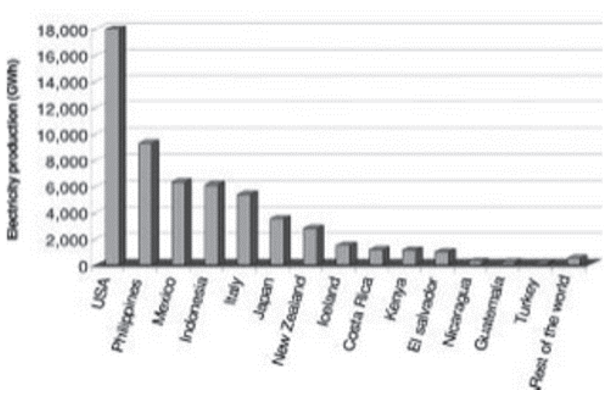


Figure 8.5 Geothermal electricity production, 2005. (Source: Bertani, R. [103].)

- 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:

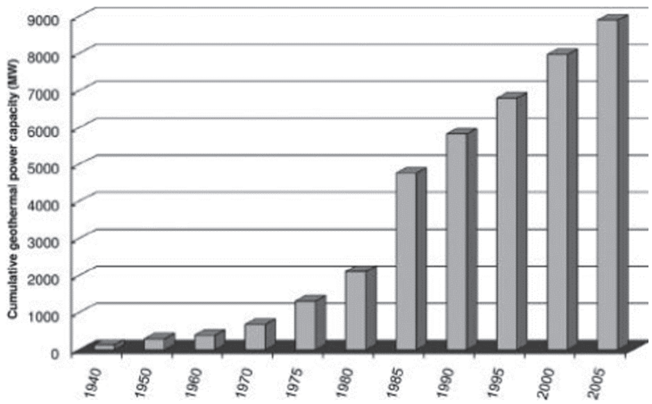


Figure 8.6 Worldwide development of geothermal electric power.

Total Source	GW (year 2018)
Coal	2,167
Natural Gas	1,769
Hydro-electric	1140
Wind	524
Liquid Fossil Fuel	381
Nuclear	374
Solar	352
Other Renewable (Biomass)	290
Geothermal	**19**
Total	7016

but total production capacity, about **19 GW (or 19,000 MW) in 2018**, 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?

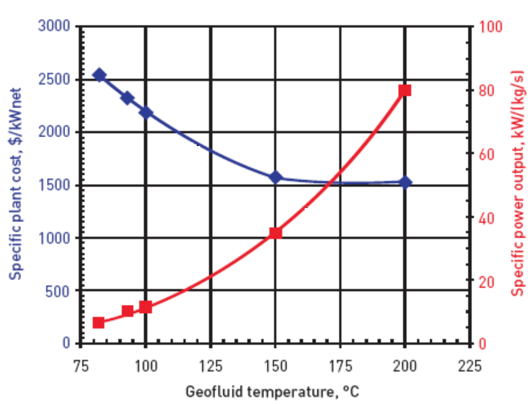
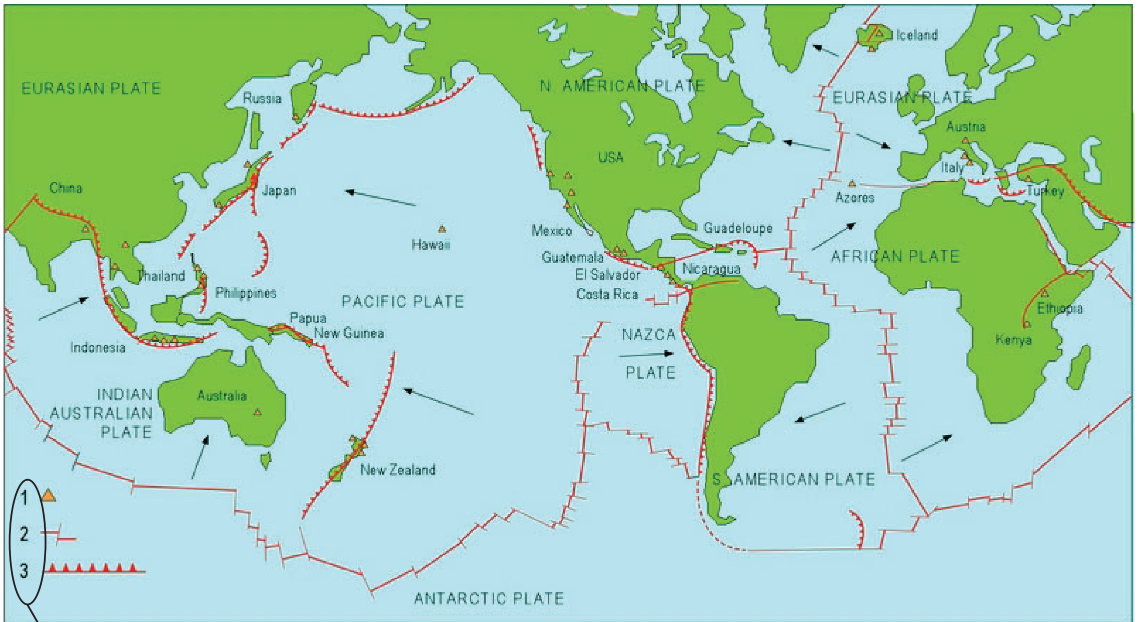


Figure 7.4 Cost and performance of 1 MW binary power plants as a function of geofluid temperature in degrees Celsius (°C).

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

Geothermal

- **Margins of tectonic plates most favorable**



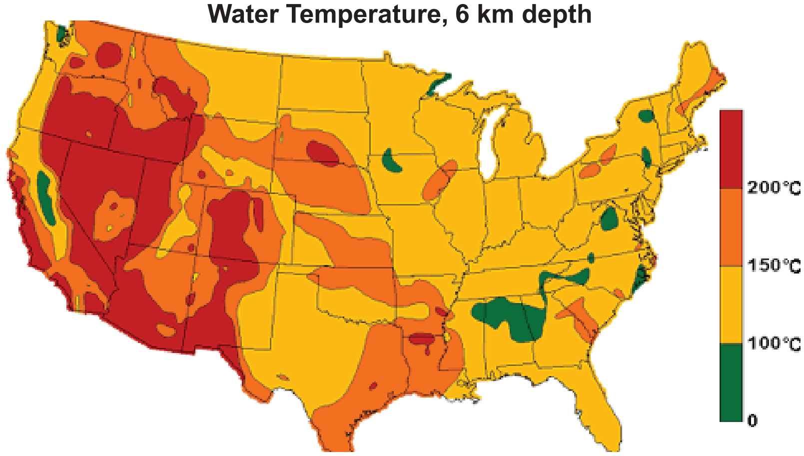
(1) Geothermal fields producing electricity http://iga.igg.cnr.it/geo/geoenergy.php
(2) mid-oceanic ridges crossed by transform faults (long transversal fractures)
(3) subduction zones, where the subducting plate bends downwards and melts in the asthenosphere (~100 to 200 km below surface)

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

Water Temperature, 6 km depth



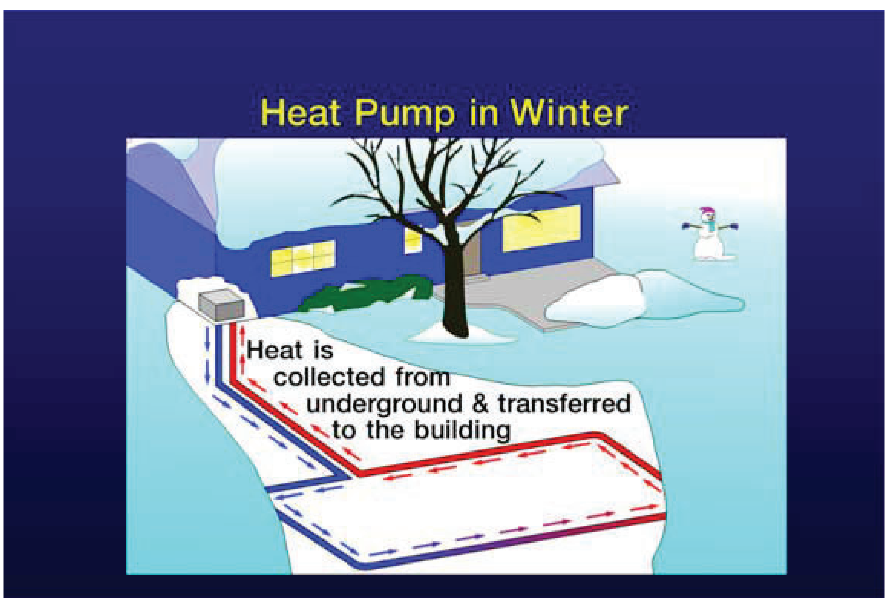
http://www1.eere.energy.gov/geothermal/geomap.html

Geothermal Heating

About 95% of the buildings in Reykjavik are heated with geothermal water.
Reykjavik is one of the cleanest cities in the world.

http://geothermal.marin.org/geopresentation/sld095.htm

Low Earth Geothermal ***Heating***



Winter: pump drives fluid to transfer energy from ground to building

http://geothermal.marin.org/geopresentation/sld102.htm

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:

0.1% of world electricity generation capacity

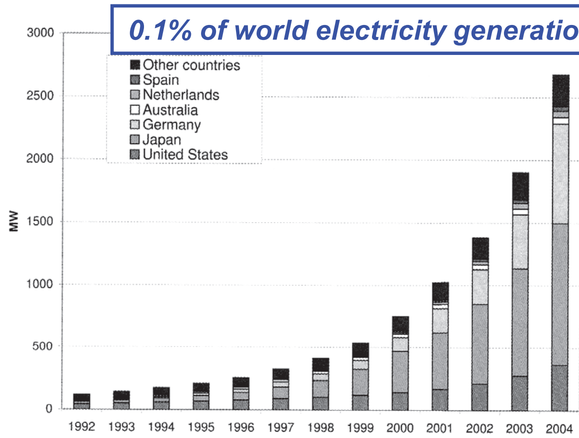


Figure 8.10 Cumulative installed photovoltaic (PV) power in reporting IEA countries. (Source: IEA-Photovoltaic power systems programme.)

5% of world electricity generation capacity

Recent Trends

Year	Solar MW
2005	**3,991**
2007	8,180
2009	22,000
2011	69,000
2013	135,000
2015	214,000
2017	247,000
2018	**352,000**

Route 1 (south of campus), just south of the new Whole Foods
22.7 kW system (**power**) has generated 227,128 kW-hours (**energy**) since 22 July 2010

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

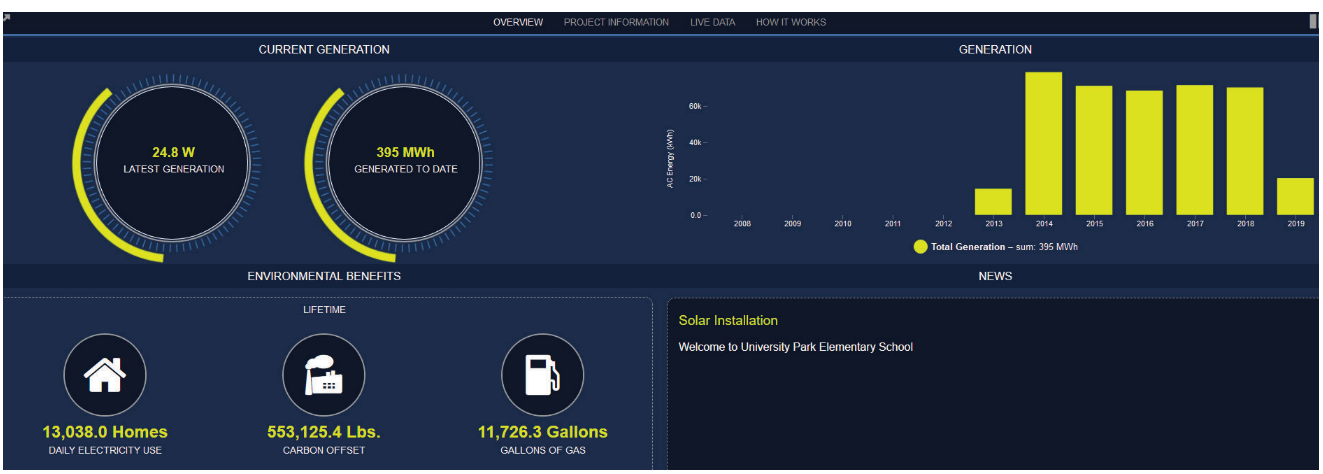
Solar PV Efficiency

Operational for:
2010: 205
2011: 365
2012: 366
2013: 365
2014: 365
2015: 365
2016: 366
2017: 365
2018: 365
2019: 113
Total: 3240 days

22.7 kW $\times$ 3240 days $\times$ 24 hrs/day= 1.84 $\times$ 10^6 kW hr

Capacity Factor = 2.27×10^5 kW hr /1.84×10^6 kW hr = **0.123**

Financial return = 2.27×10^5 kW hr $\times$ 0.13 \$/kW hr = **\$29,510**

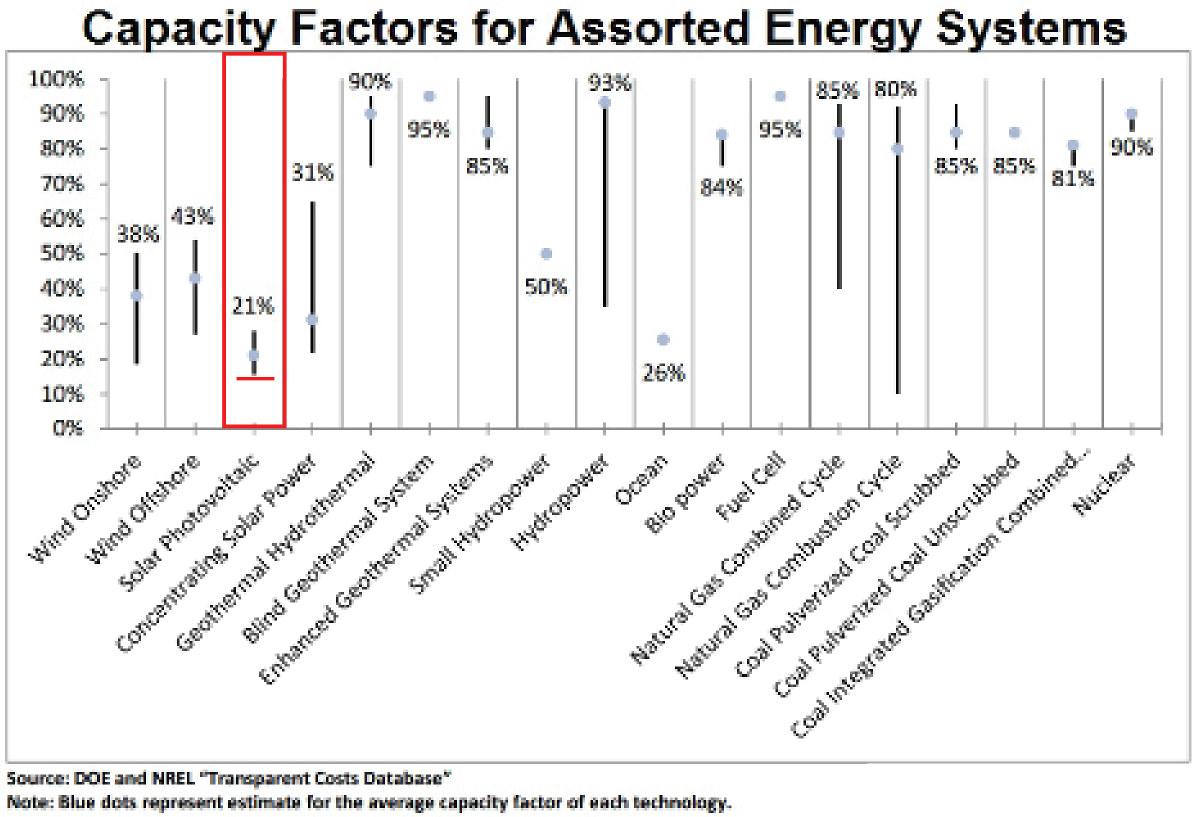


http://kiosk.datareadings.com/elkWdi6e/overview?granularity=total&slideshow=true

64.8 kW $\times$ 2018 days $\times$ 24 hrs/day= 3.14 $\times$ 10^6 kWh

Capacity Factor = {395 MWh $\times$(10^3 kWh/MWh)} / 3.14×10^6 kWh = **0.126**

Financial return = 3.95 $\times10^5$ kW hr $\times$ 0.13 \$/kW hr = **\$51,350**



http://www.lightevolution.co.uk/blog/geothermal-visual-capacity-factors-for-assorted-energy-systems/

Solar PV Efficiency

A second challenge is that the direct conversion of sunlight into electricity is not very efficient. A photovoltaic cell could, in principle, transform up to 31% of the radiant energy to which it is sensitive into electricity.

Page 357, *Chemistry in Context*

- Known as the Shockley–Queisser limit due to pioneering study by William Shockley and Hans-Joachim Queisser in 1961.
- Refers to the maximum theoretical efficiency of a solar cell using a single p-n junction.
- Energy limit due to:

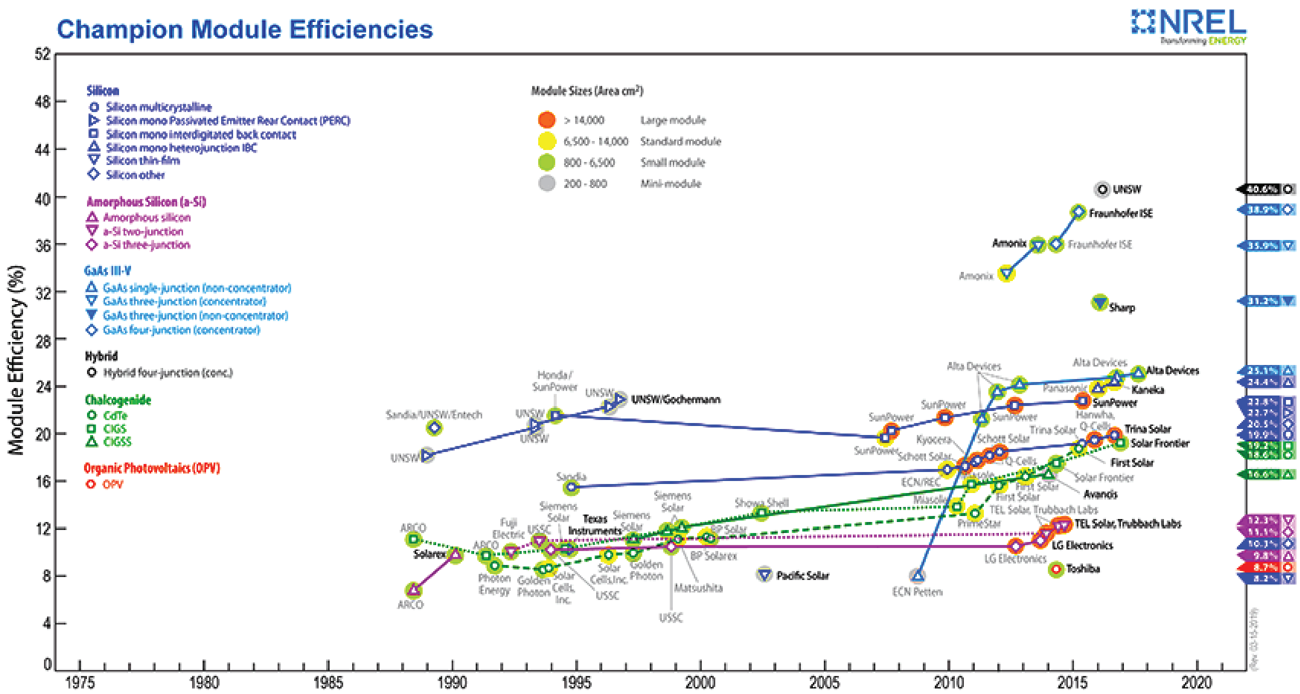
Physics: Absorption of a photon creates an electron-hole pair, which could potentially contribute to the current. However, the reverse process must also be possible; an electron and a hole can meet and recombine, emitting a photon

Radiation: At least about 7% of the incoming energy will be converted to heat and radiated

Enthalpy: Since moving an electron from the valence band to the conduction band requires energy, only photons with more than that amount of energy will produce an electron-hole pair. Simply put, a single junction will be preferentially tuned to photons of a specific wavelength; more energetic light can contribute (albeit, with diminished efficiency) whereas less energetic light not displace any electrons.

https://en.wikipedia.org/wiki/Shockley–Queisser_limit

Solar PV Efficiency



https://cleantechnica.com/2019/03/30/most-efficient-solar-modules-nrels-new-chart

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

https://web.archive.org/web/20170728233529/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 MWh / year

Construction cost: $266 million or

~$2 / kWh for one year's prod

Nevada Solar One

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

Project output for 2008 to 2018: **1,313,500 MWh** (energy, or power × time)

Number of hours in year = 365×24 = 8760 h

Capacity Factor = 1,313,500 MWh / (64 MW × 8760 h/yr × 11 yrs) = **0.21**

Nevada Solar One

Output: 64 MW capacity

Could supply all of US electricity needs in 2017 if built over a 144 mile × 144 mile area

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

Generation (MW·h) of Nevada Solar One

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

Note: 1 GWh = 1000 MWh

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
2016	116.89	2.24	119.13
2017	118.03	2.58	120.60
2018	110.38	2.57	112.95

2018 was 17% lower than 2010 peak

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.

Solar Energy

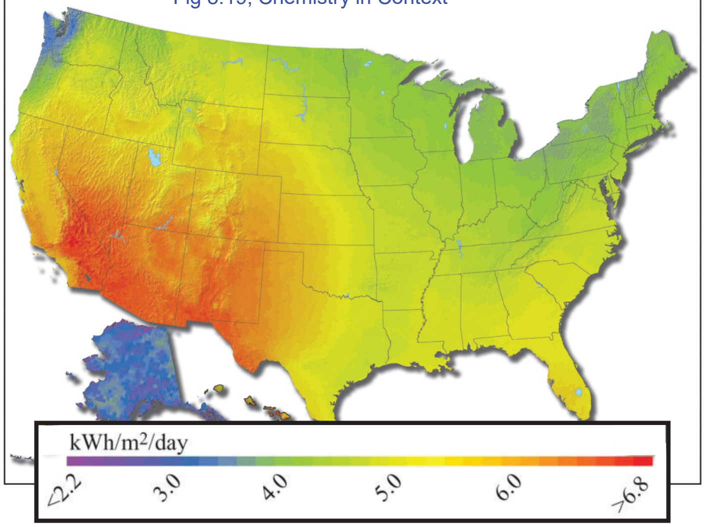
At currently attainable levels of operating efficiency, the electricity needs of the United States have been estimated to require a photovoltaic generating station covering an area of 85 miles by 85 miles, roughly the size of New Jersey.

Page 358, *Chemistry in Context*

Using the current solar technology, an area of 160 × 160 km in this region [the Mojave Desert] could generate as much energy as the entire U.S currently consumes.

Page 123, *Olah et al.*

Fig 8.19, Chemistry in Context



Olah et al. state:
On a clear day, Earth receives about 1000 W m^{-2} at noon
In the US, the highest [solar] insolations have a daily average in excess of 6 kWh m^{-2}

Let's assume 6 kWh m^{-2}

In 2018, US used 3802×10^6 MWh = 3802×10^9 kWh of electricity

https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_01

Would need an area of:
$\{3802 \times 10^9 \text{ kWh}/(6 \text{ kWh m}^{-2} \times 365)\}^{1/2}$ = 42 km by 42 km
if we could capture the full 6 kWh m^{-2}

Area is 93 km × 93 km with 20% capacity factor
117 km × 117 km with 12.5% " "

Nevada Solar One / US Energy Needs

US Electricity Consumption is 3802 TWh or 3802×10^6 MWh

https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_01

Nevada Solar One output last 5 years: 113,000 MWh

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

To meet US Energy Needs, would need an area of:
$(3802 \times 10^6 \text{ MWh} / 113{,}000 \text{ MWh}) \times 0.6$ square mile = 2×10^4 square miles

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

Cost: \$2 / KWh × 3802 TWh × (10^9 KW/TW) = \$ 7.6×10^{12} or **\$7.6 trillion dollars**

US GDP in 2018 was **\$20.9 trillion dollars**