Renewable Energy I: Hydro, Wind and Solar

AOSC / CHEM 433 & AOSC / CHEM 633

Ross Salawitch

Class Web Sites:
http://www2.atmos.umd.edu/~rjs/class/fall2020
https://myelms.umd.edu/courses/1291919

Next three lectures:
Pros and cons of meeting energy needs by means other than the combustion of fossil fuel

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

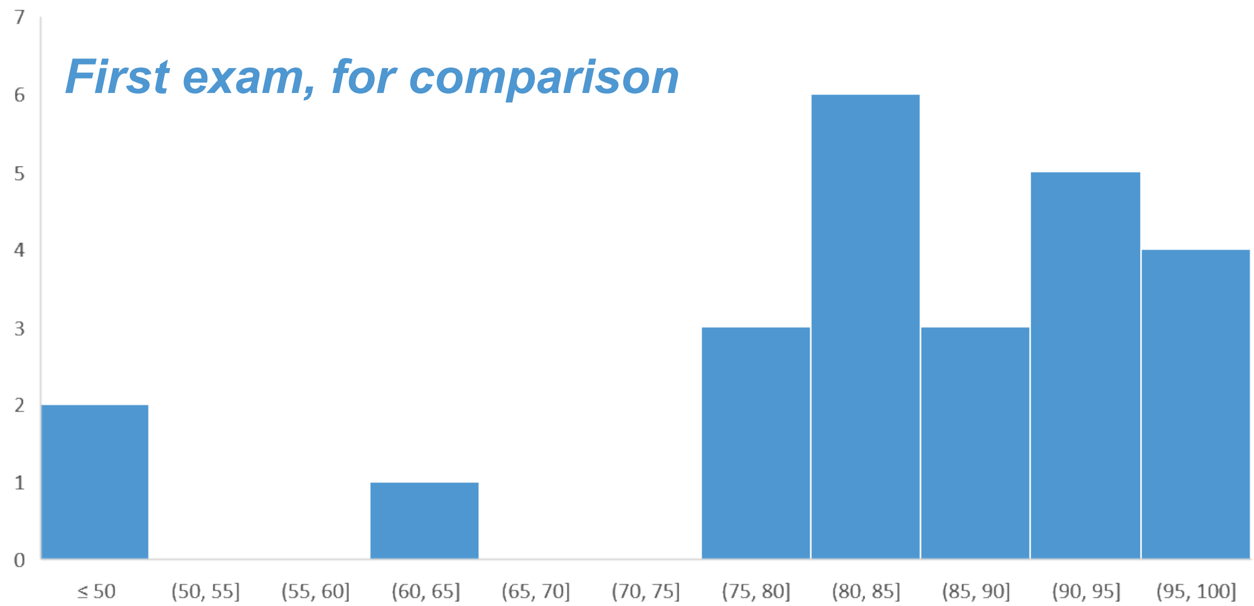
Lecture 19

24 November 2020

Student Papers

- **Mandatory for 633 students:** paper grade will count towards final grade in an amount equal to each exam
- **Optional for 433 students:** can use paper grade to replace a ***single*** problem set grade: advisable for anyone who failed to turn in a problem set or would otherwise like to replace the grade on a problem set
- **Due Thursday, 10 Dec 2020 (last day of class)**
- **5 to 8 pages** single spaced (not including reference list or figures) on a topic related to class (your choice …we're happy to discuss potential topics)
- Must be ***new work for this class*** but can be related to your dissertation or some other topic in which you've had prior interest
- Paper can build on a topic covered in class or can be on a topic related to Atmospheric Chemistry & Climate not covered in class: should have about 5 to 10 citations to material outside of that provided in class
- Request all students who will complete a paper provide a **2 to 3 sentence description of their topic one week** from today: **Tues, 3 Nov 2020**
  https://umd.instructure.com/courses/1291919/quizzes/1351196
  Please use next week to speak to exchange email with me about a topic
- Delighted to provide feedback on your paper, if given the opportunity: i.e., if you turn in a draft at least by 11:59 pm on Tues, 1 Dec.

Both 433 & 633 Exam Scores



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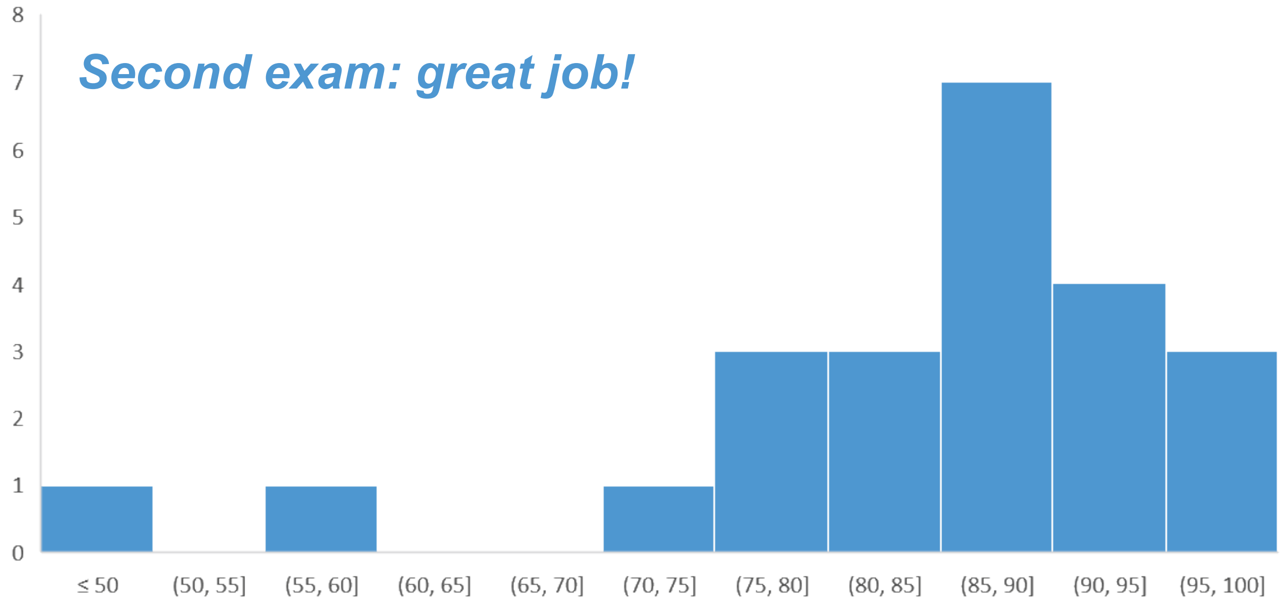
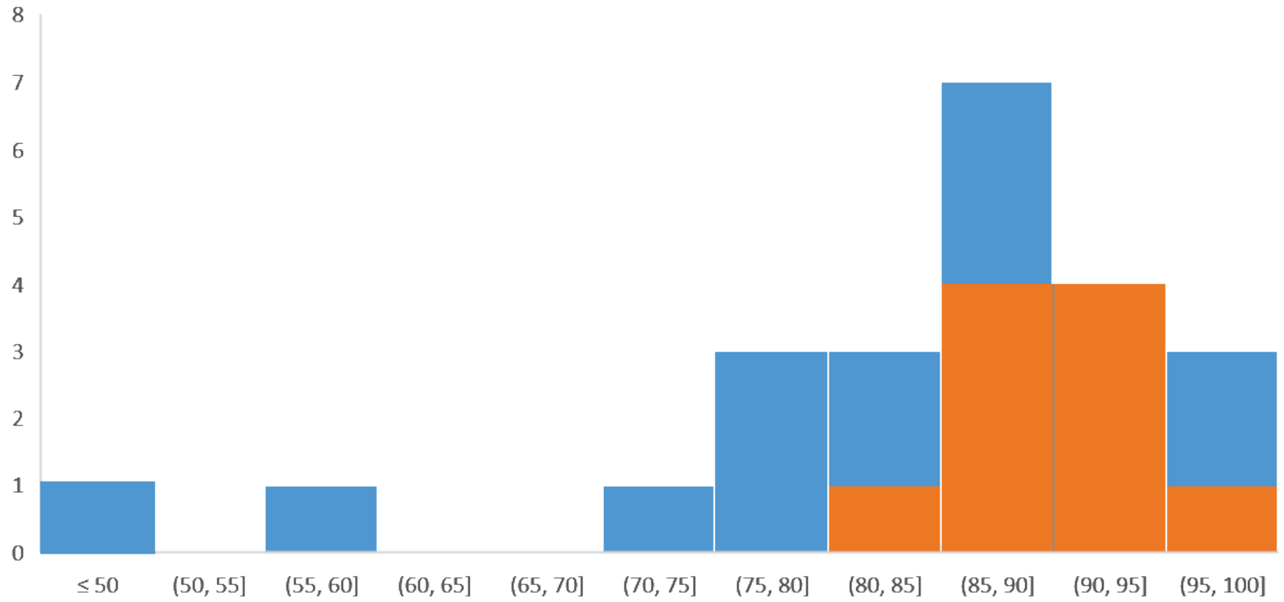
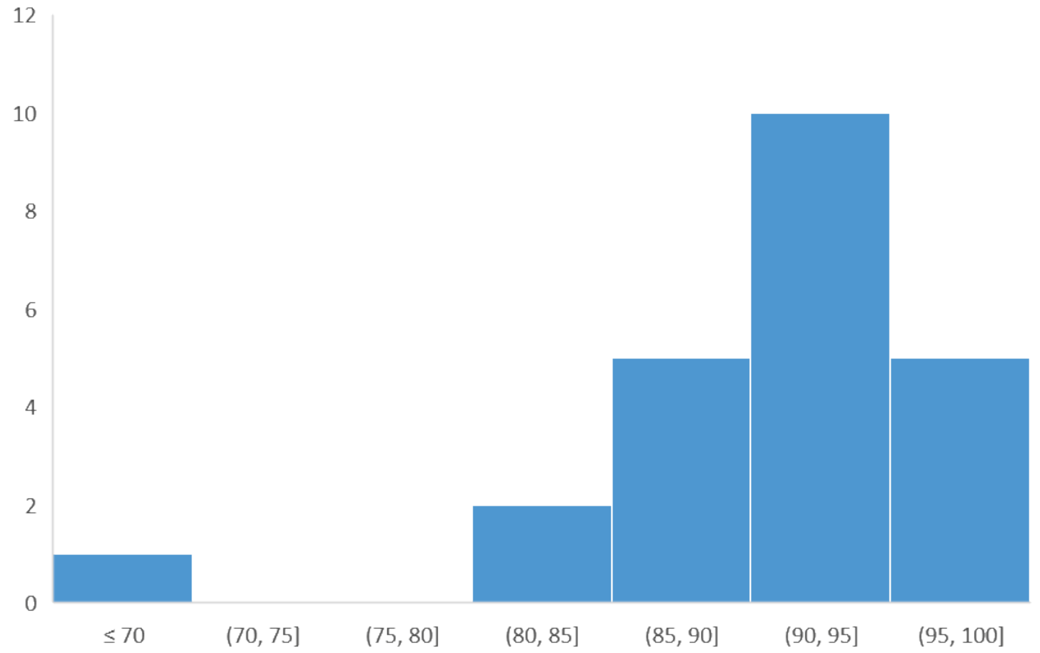


Both 433 & 633
633 in Orange



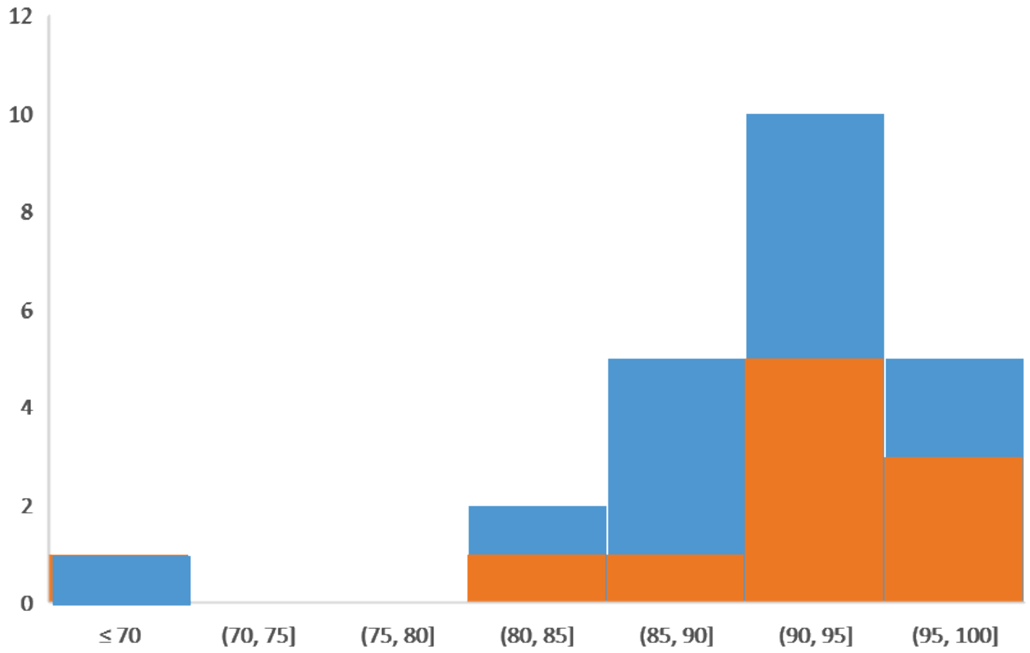
Overall

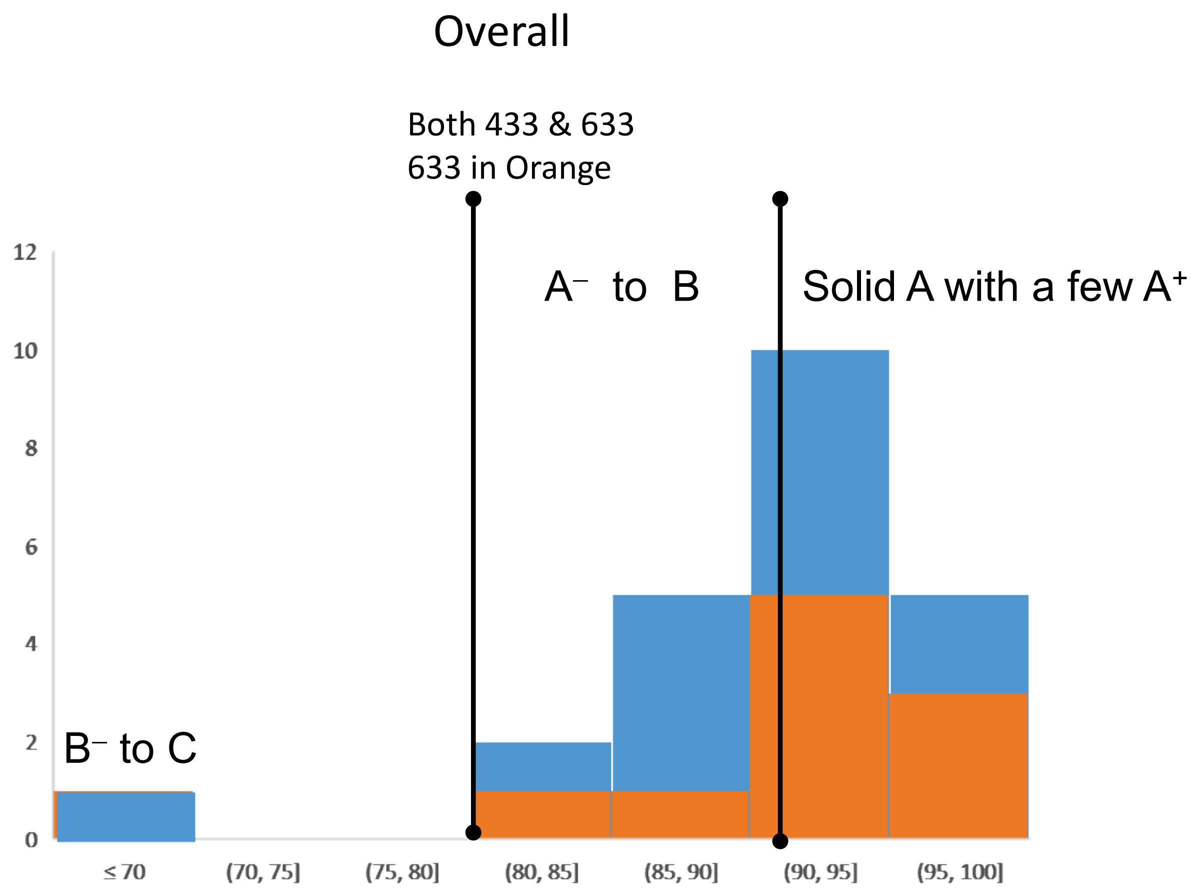
Both 433 & 633



Overall

Both 433 & 633
633 in Orange




Overall
Both 433 & 633
633 in Orange
A⁻ to B
Solid A with a few A⁺
B⁻ to C
12
10
8
6
4
2
0
≤ 70
(70, 75]
(75, 80]
(80, 85]
(85, 90]
(90, 95]
(95, 100]

Energy and Power

Simple equation connects energy and power:

Energy = Power $\times$ 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 & Electricity Supply

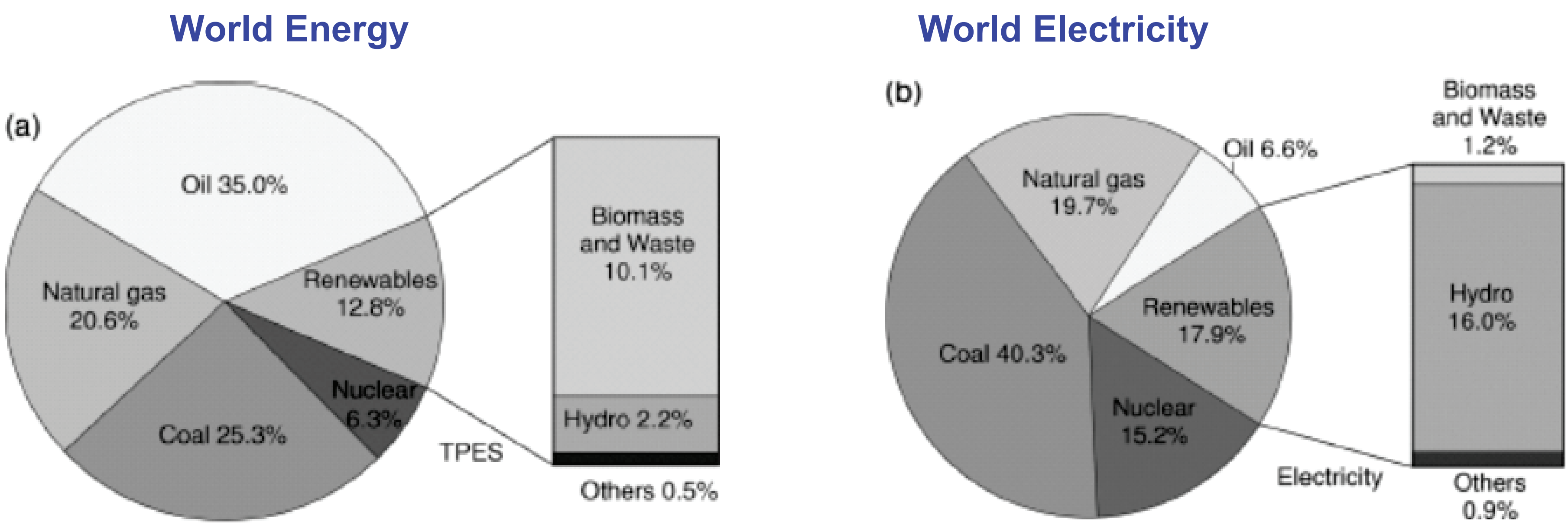


Figure 8.1 (a) Share of renewables in the world total primary energy supply (TPES) in 2005; (b) share of renewables in world electricity production in 2005. (Source: IEA Renewables Information 2007.)

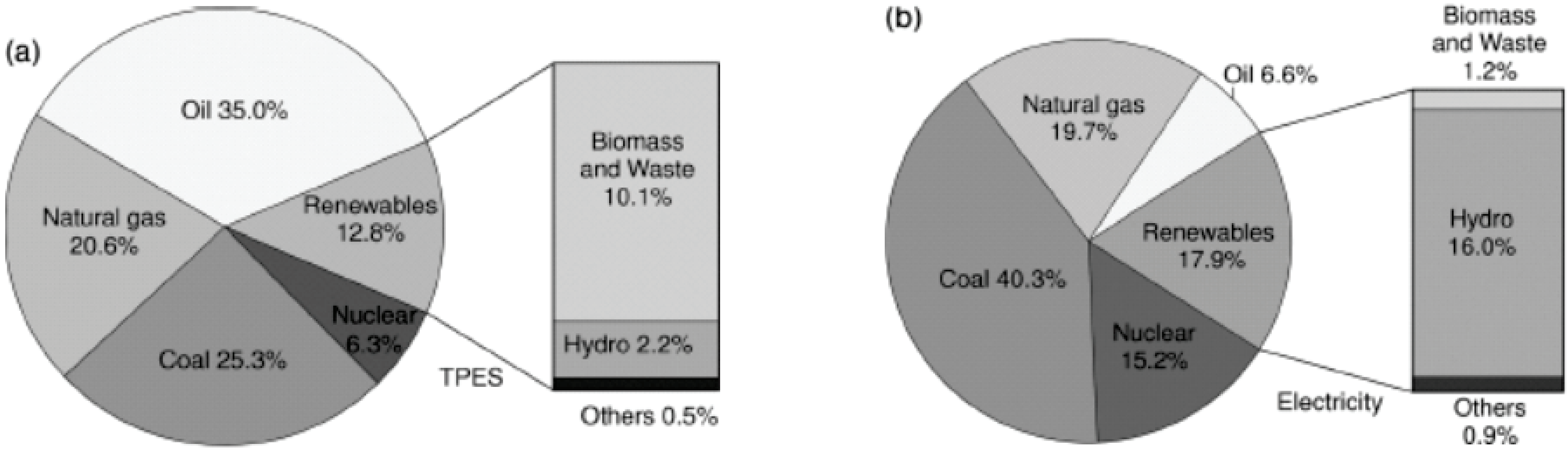
Olah *et al.*, *Beyond Oil and Gas: The Methanol Economy*, 2009

In 2005, world obtained:
~80% of its **energy** &
~66% of its **electricity**
from combustion of fossil fuels

World Energy & Electricity Supply: units of Energy

World Energy

World Electricity



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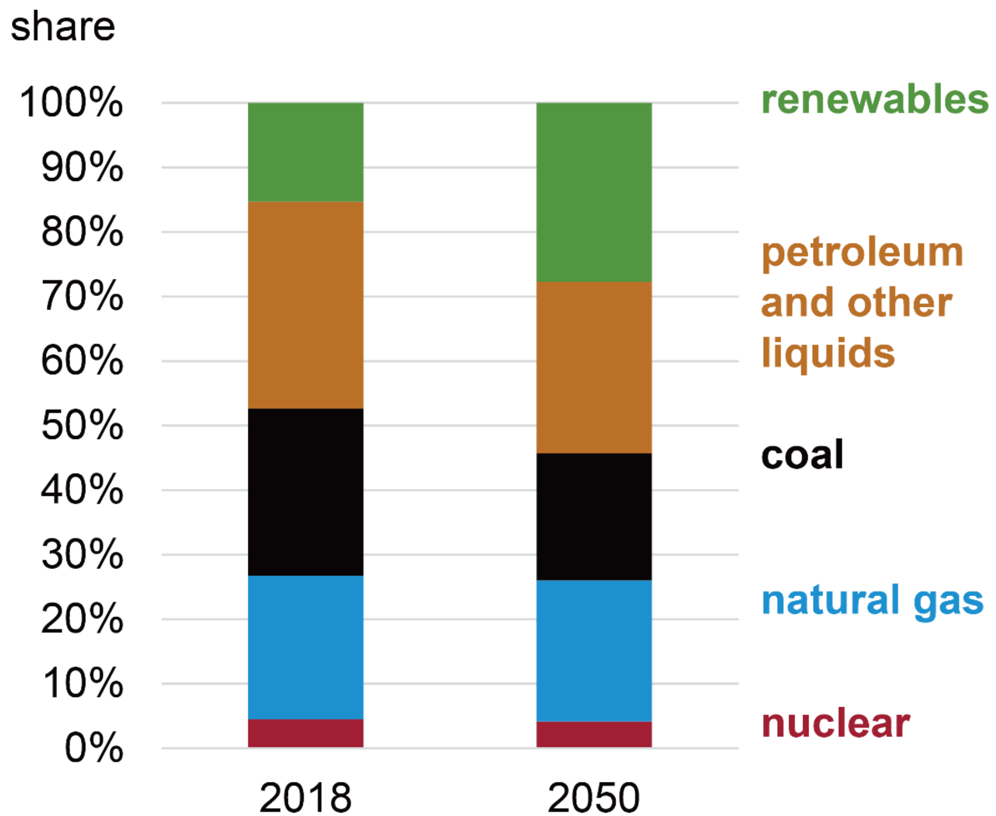
Olah *et al.*, *Beyond Oil and Gas: The Methanol Economy*, 2009

In 2005, world obtained:
~13% of its **energy** &
~18% of its **electricity**
from renewable sources

World Energy Supply Update & Projection: units of Energy



In 2018, world again still obtained
~80% of its **energy**
from combustion of fossil fuels

https://www.eia.gov/outlooks/ieo/pdf/ieo2020.pdf

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

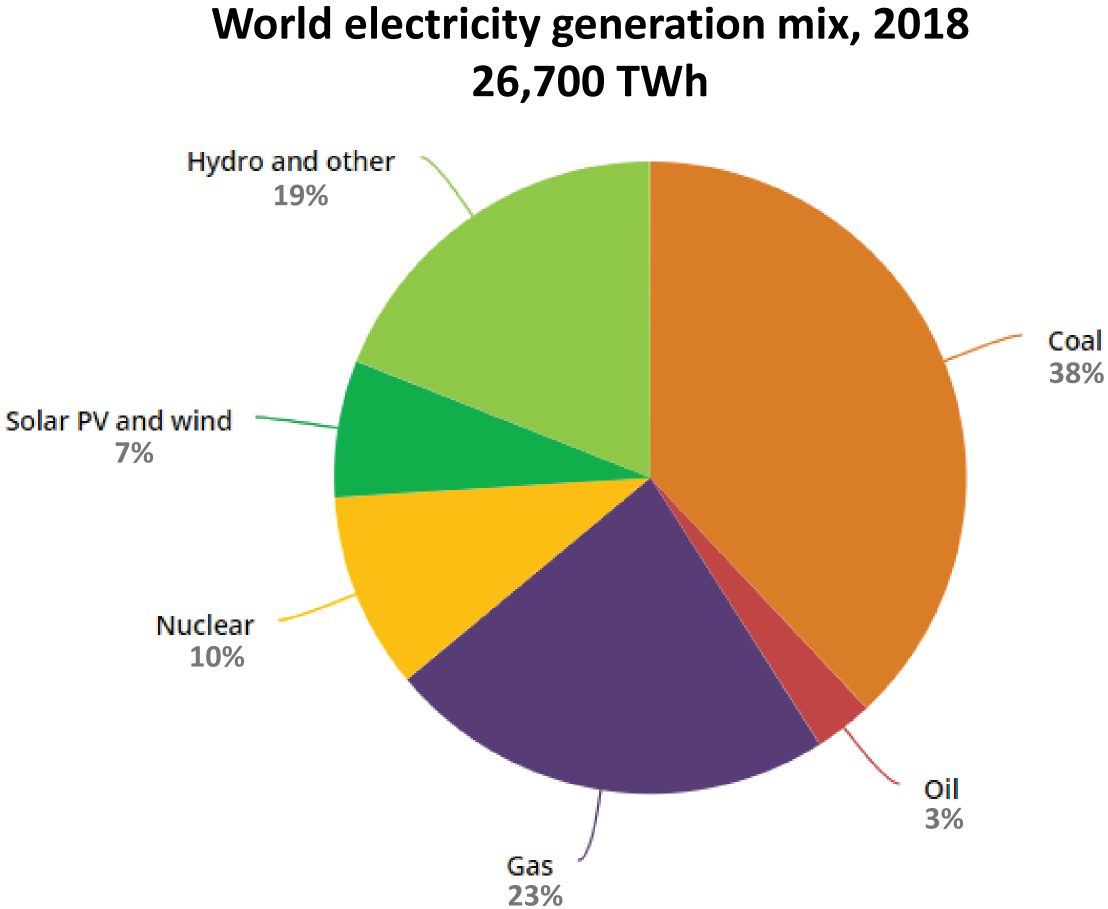
Power (Energy/Time)

Total Source	GW (year 2020)
Coal	2154
Natural Gas	1662
Hydro-electric	**1262**
Solar	**700**
Wind	**646**
Nuclear	374
Liquid Fossil Fuel	297
Other Renewable (Biomass)	121
Geothermal	**13**
Total	7229

Source: https://www.eia.gov/outlooks/ieo/tables_ref.php

In 2020, **43%** of global ***electricity generating capacity*** does not release prodigious GHGs to the atmosphere

World Electricity Update: units of Energy



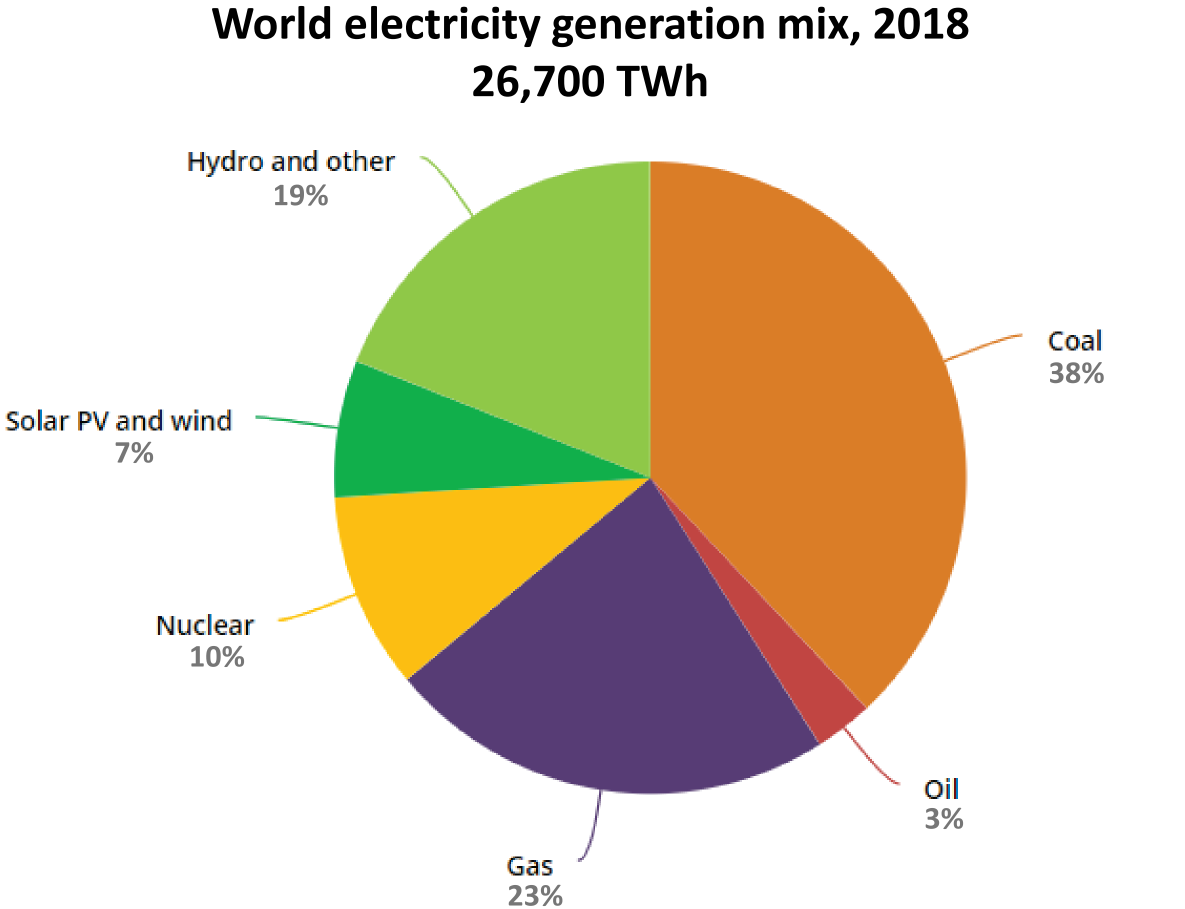
https://www.iea.org/geco/electricity/

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

Glass half empty (compare to slide 9):

In 2018, world still obtained ~64% of its **electricity** from combustion of fossil fuels

World Electricity Update: units of Energy



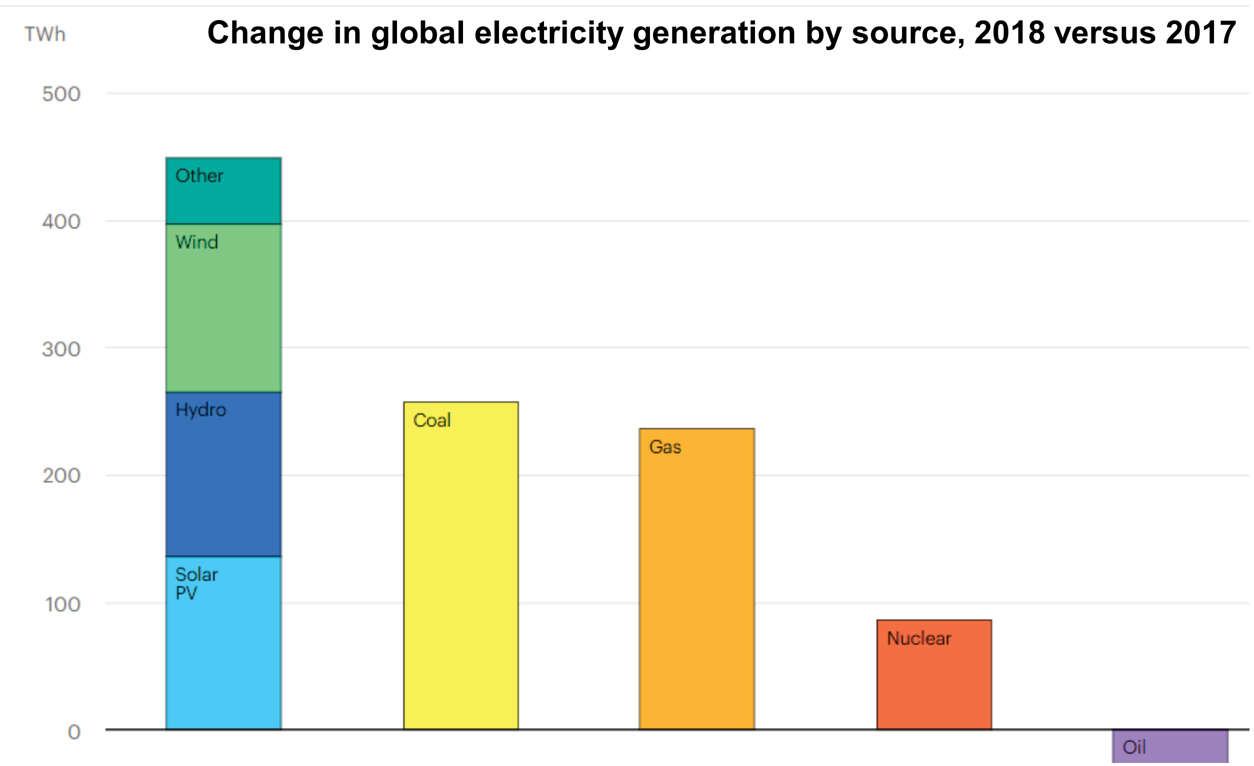
https://www.iea.org/geco/electricity/

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

Glass half full (compare to slide 10):

In 2018, world obtained ~26% of its **electricity** from renewables, compared to 18% in 2005.

World Electricity Trend



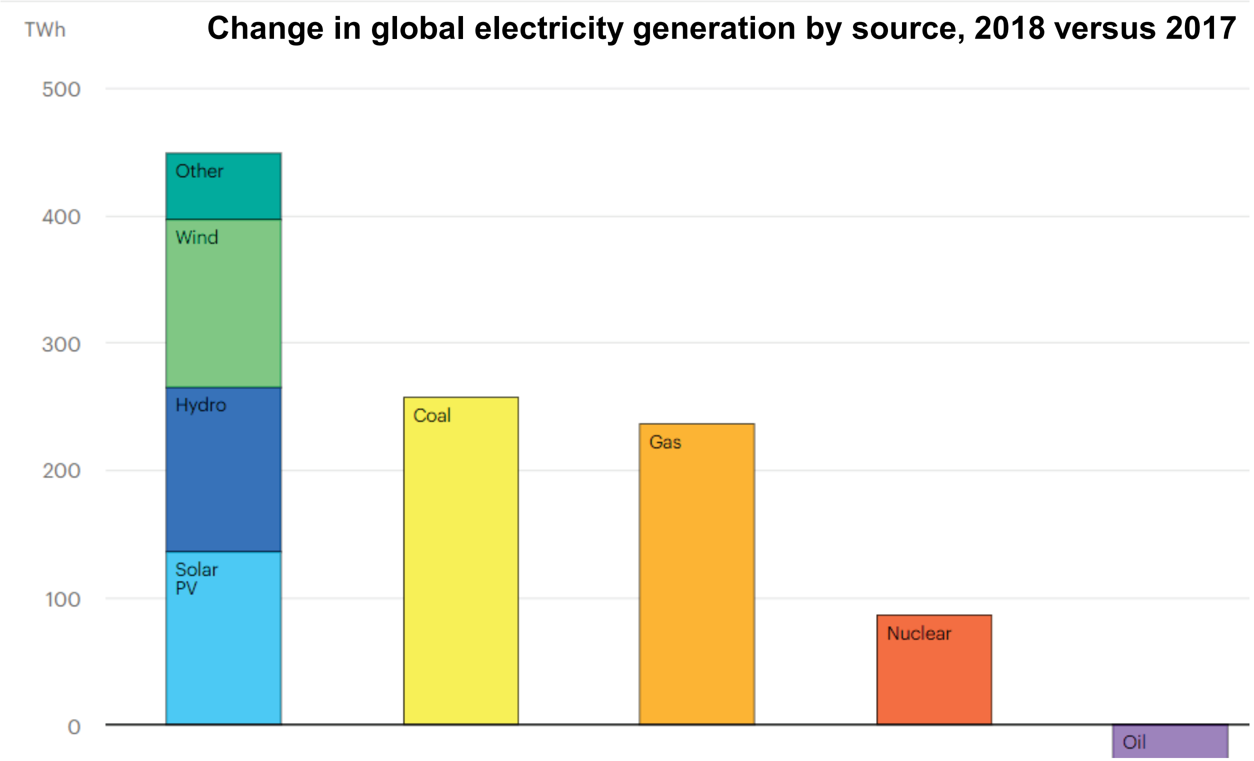
https://www.iea.org/reports/global-energy-co2-status-report-2019/electricity#abstract

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 4000 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.

World Electricity Trend



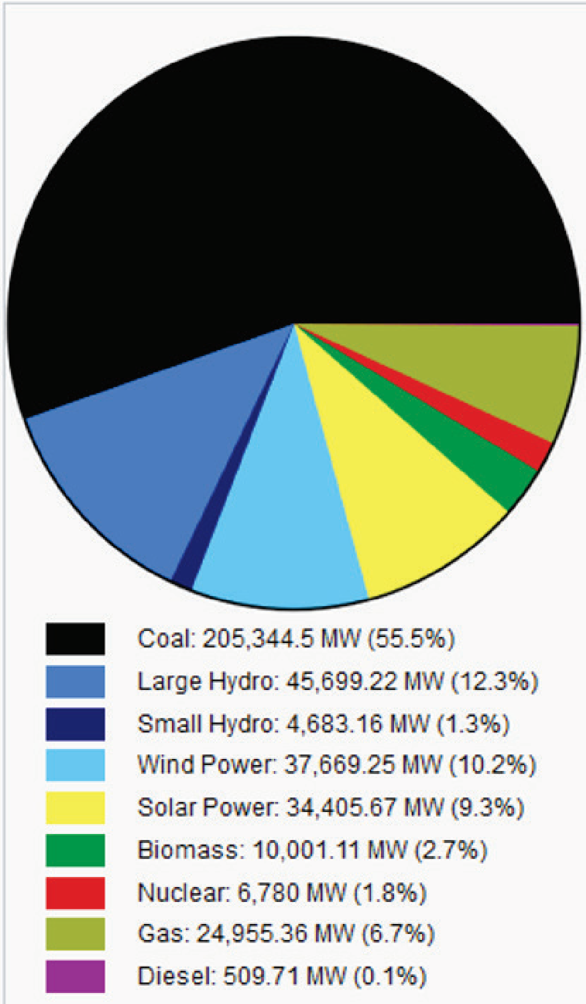
https://www.iea.org/reports/global-energy-co2-status-report-2019/electricity#abstract

India's power demand increased by around 65 TWh, or 5.4%. The increase was driven by higher demand in buildings, especially from air conditioning, as well as higher access to electricity.

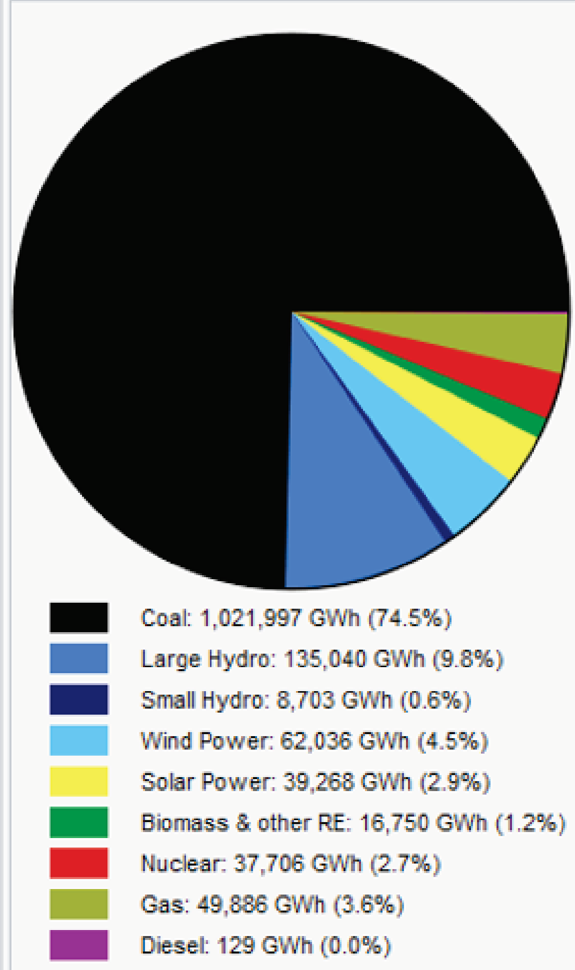
***India recently completed the electrification of all its villages*, with electricity connections extended to around 30 million people.**

Electricity Generation in India

Installed capacity by source in India as on 31 March 2020[16]

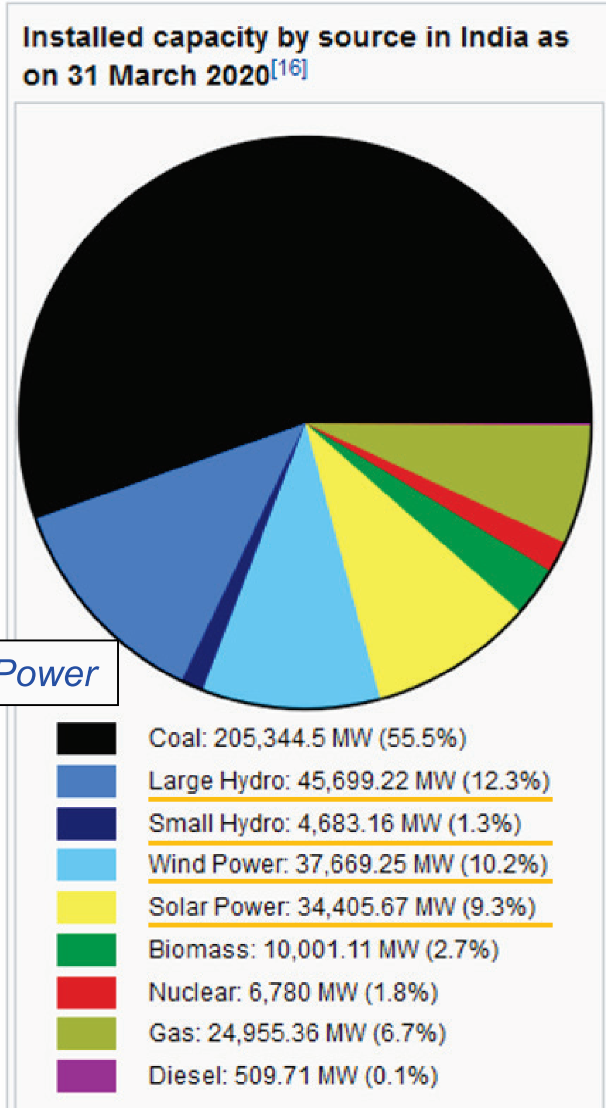


Electricity generation (utility sector) by source in India in FY 2018-19



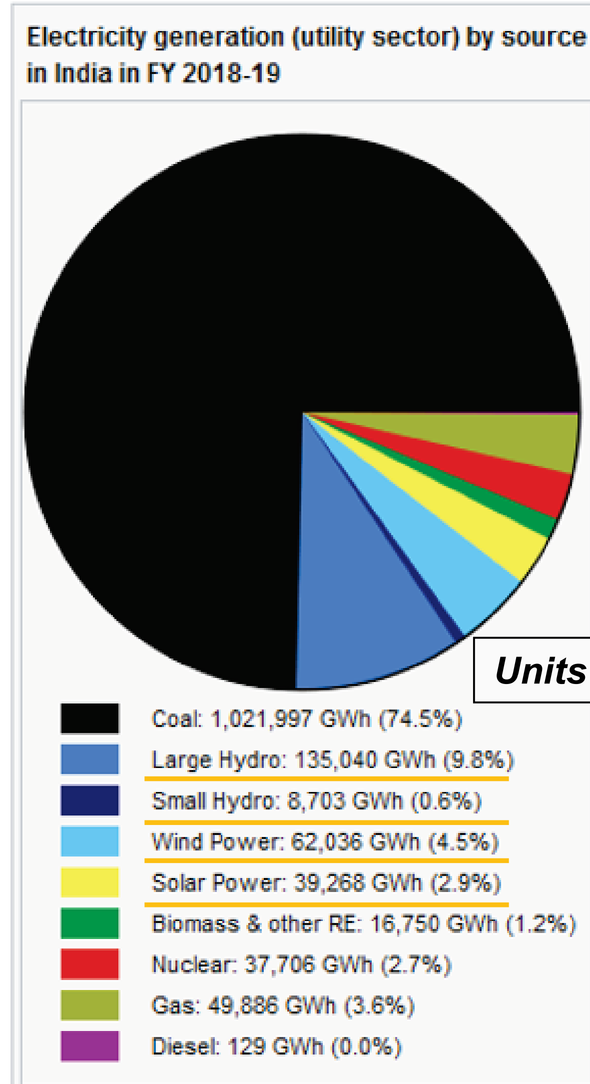
https://en.wikipedia.org/wiki/Electricity_sector_in_India

Electricity Generation in India



Units of Power

Hydro, wind, solar = 33.1 % of installed capacity

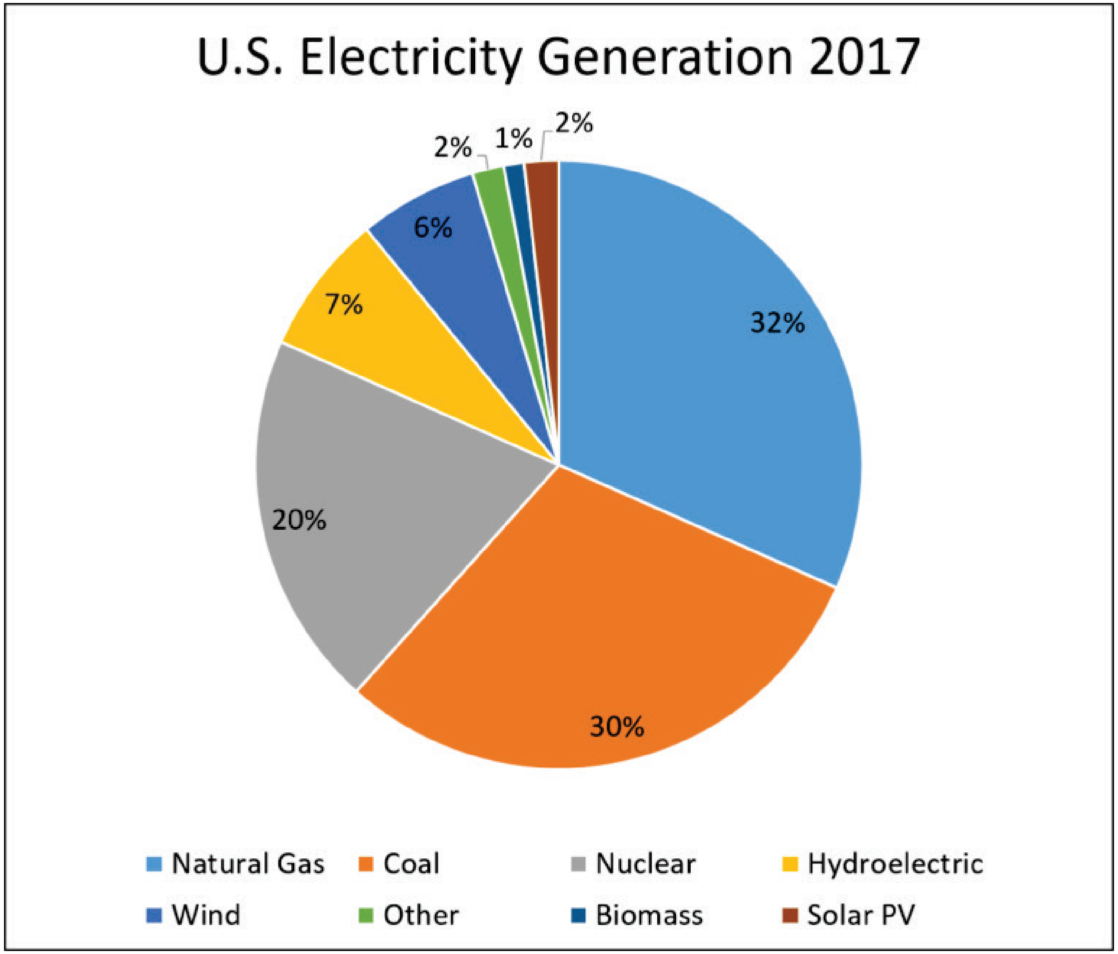


Units of Energy

Hydro, wind, solar = 17.8 % of electricity generated

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

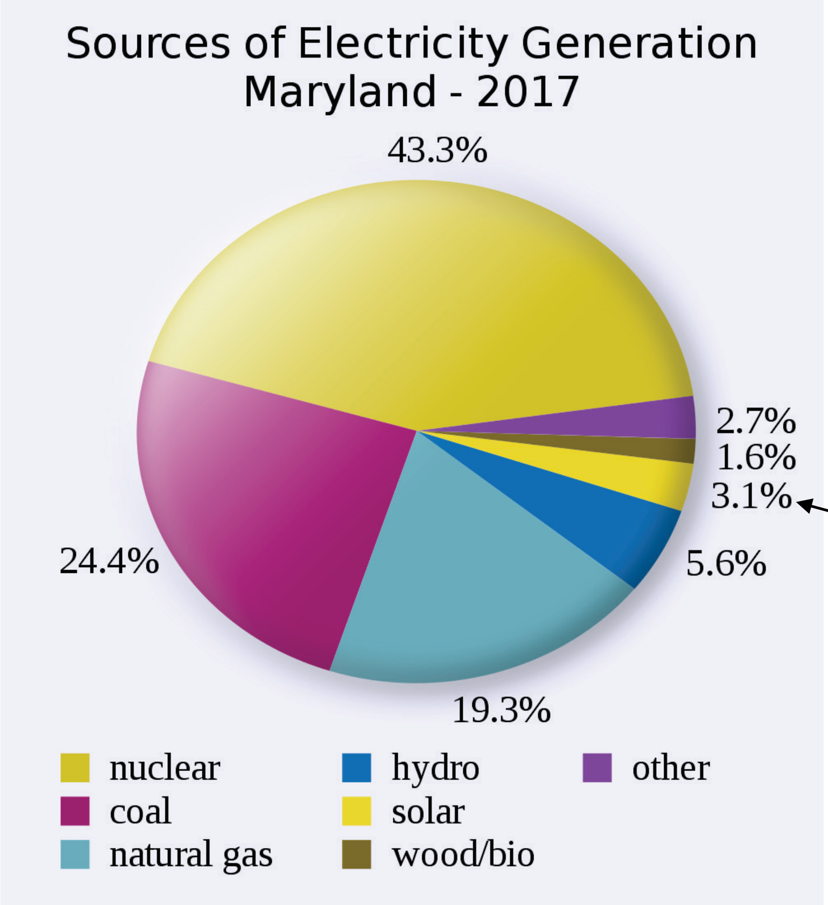
U.S. *Electricity* Supply: 2017



https://www.americanexperiment.org/2019/01/pelosi-concerned-climate-change-oppose-yucca-mountain

In 2017, the U.S. obtained ~64% of its electricity from fossil fuels & ~15% from hydro, wind and solar

MD *Electricity* Supply: 2017

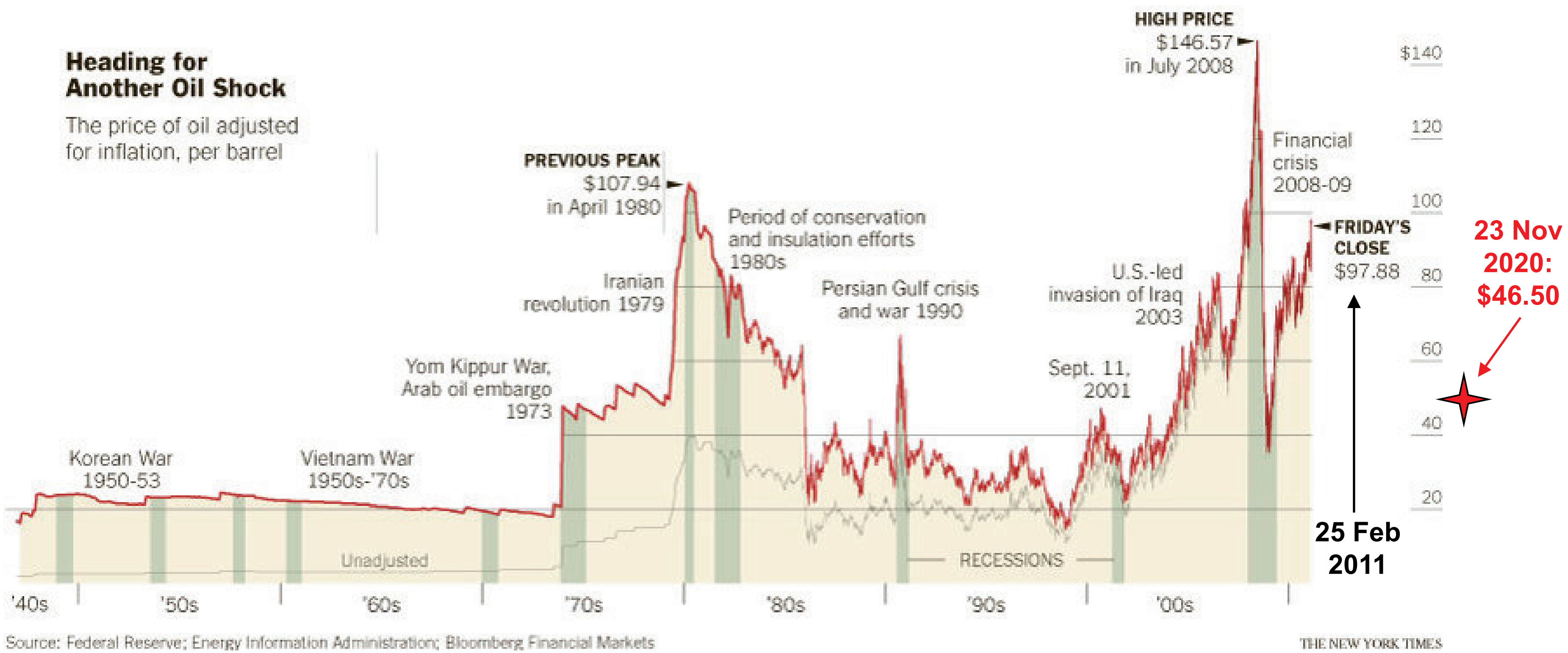


Solar: 3.1%

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 & ~11.4% from hydro, wind and solar

Market Force #1: Cost of Fossil Fuel

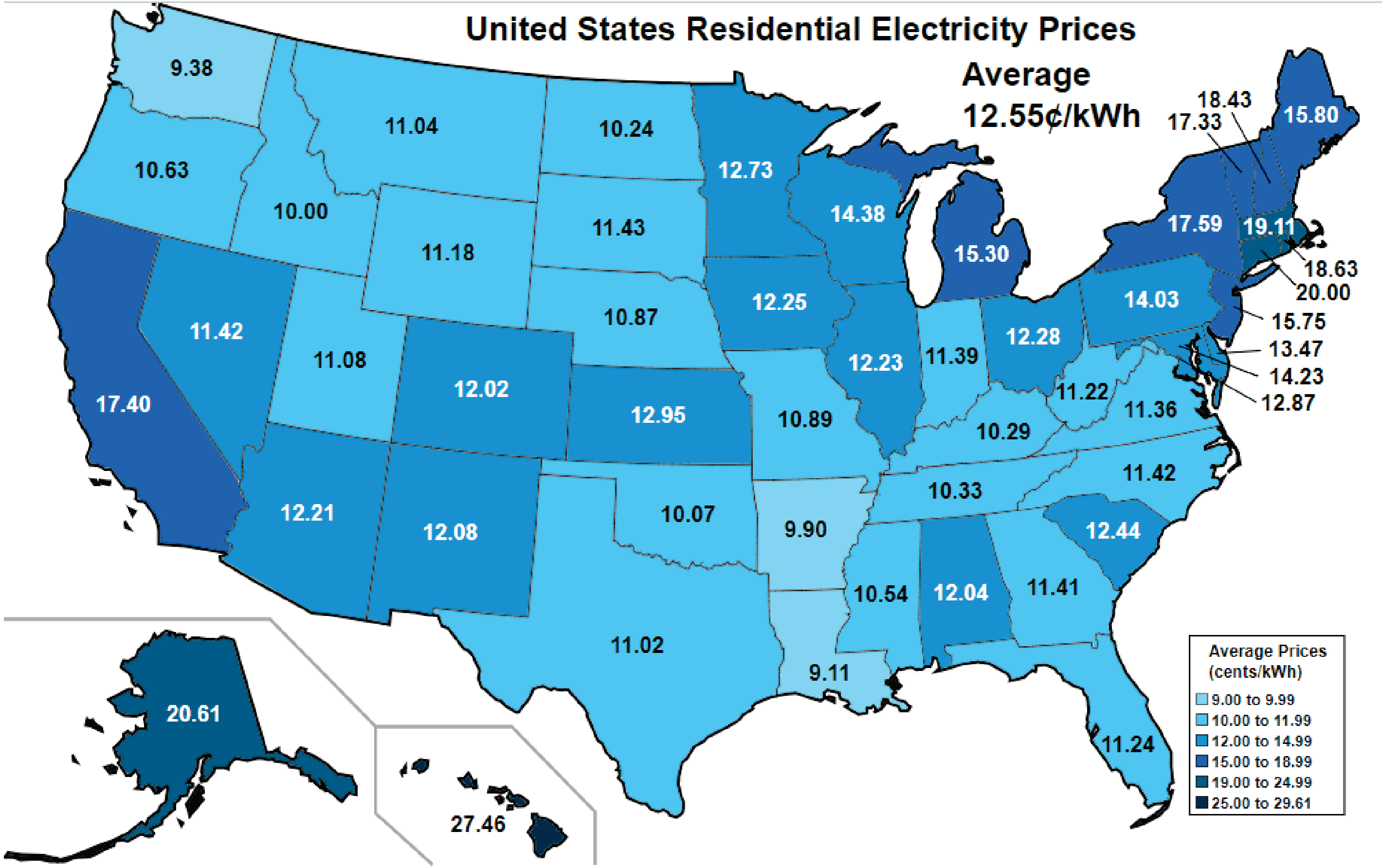


http://www.nytimes.com/2011/02/28/business/global/28oil.html

Graph shows cost of a barrel of oil

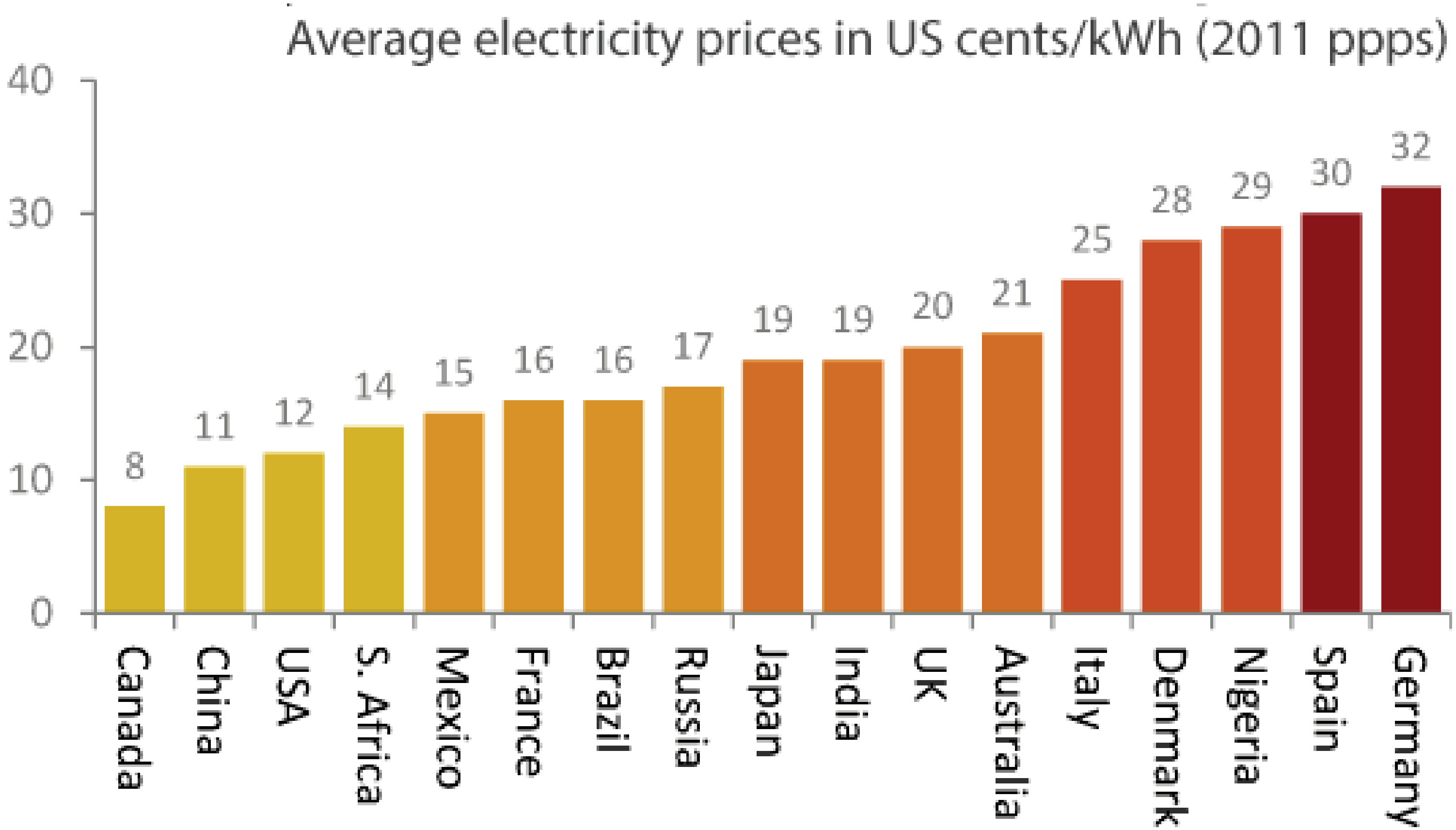
Market Force #2: Price of Electricity

**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

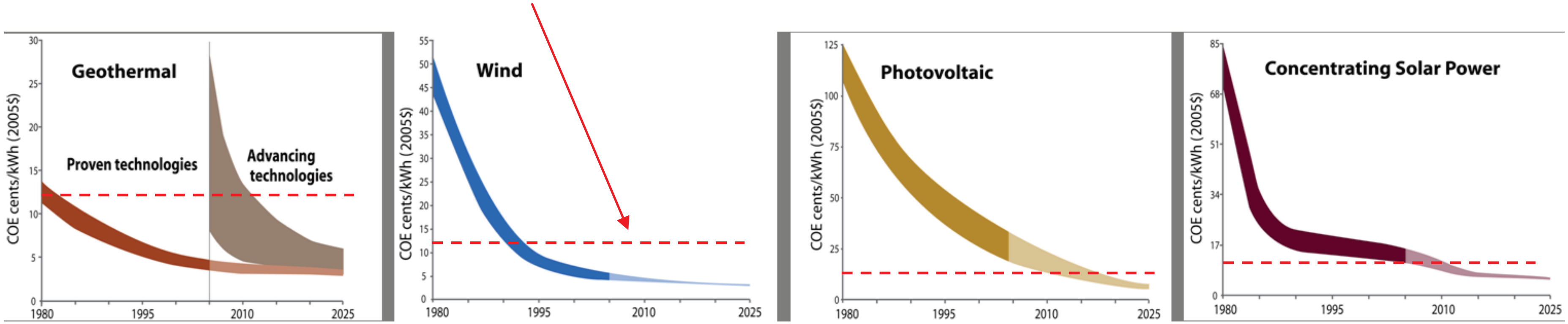


ppps: purchasing power parities

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

Market Force #3: Cost of Electricity from Renewables ↓

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

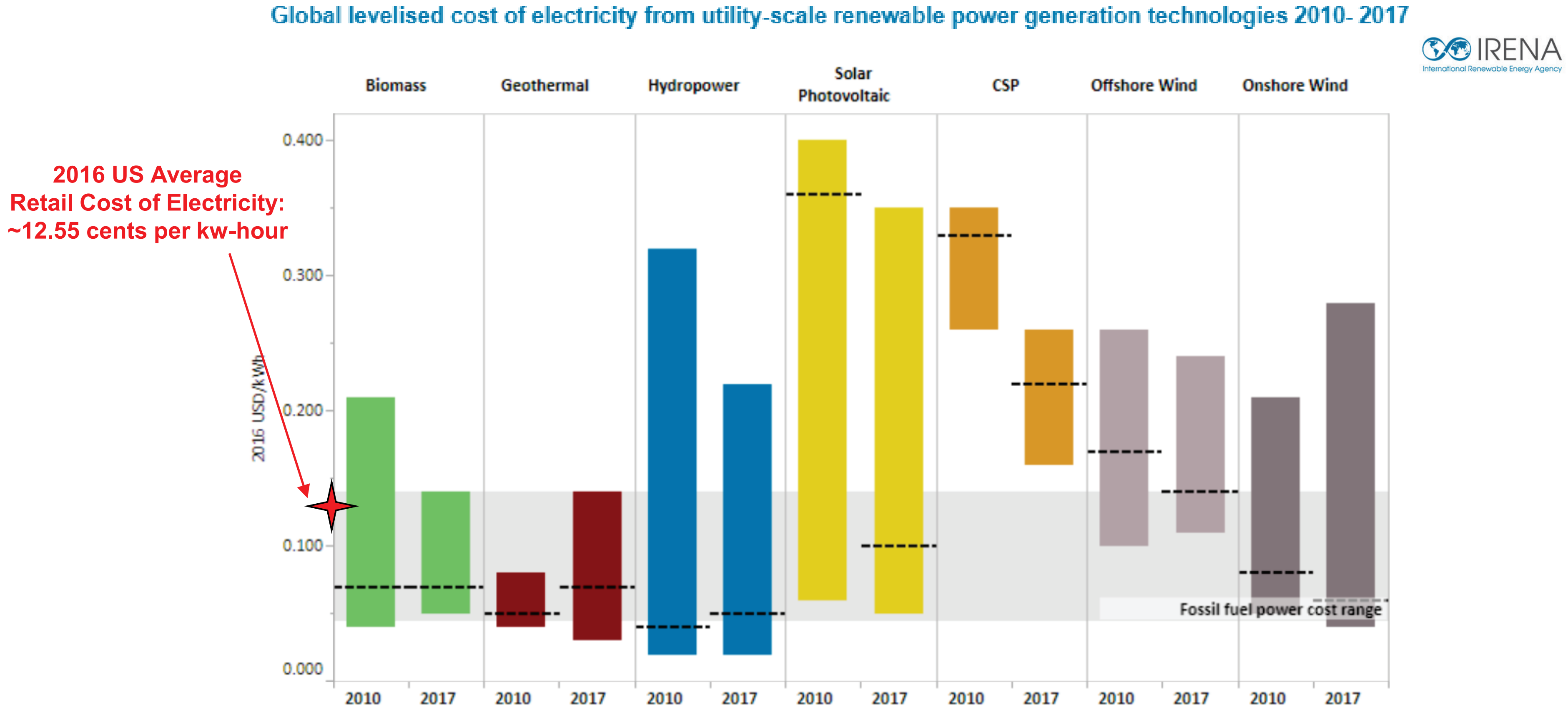


National Renewable Energy Lab: http://www.nrel.gov/analysis/docs/cost_curves_2005.ppt

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 #3: Cost of Electricity from Renewables ↓



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

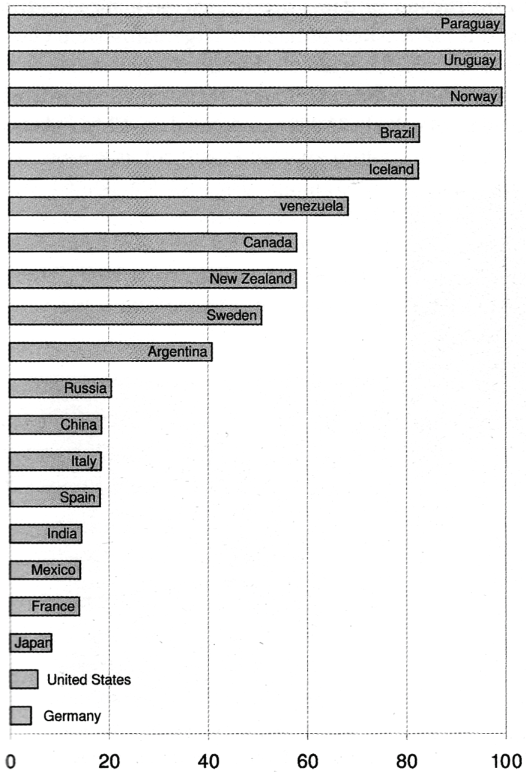


Figure 8.2 Percentage of electricity produced from hydropower in different countries. (Source: CIA World Factbook, December 2003.)

Hydro: 17 % of world electricity capacity

Total Source	GW (year 2020)
Coal	2154
Natural Gas	1662
Hydro-electric	**1262**
Solar	700
Wind	646
Nuclear	374
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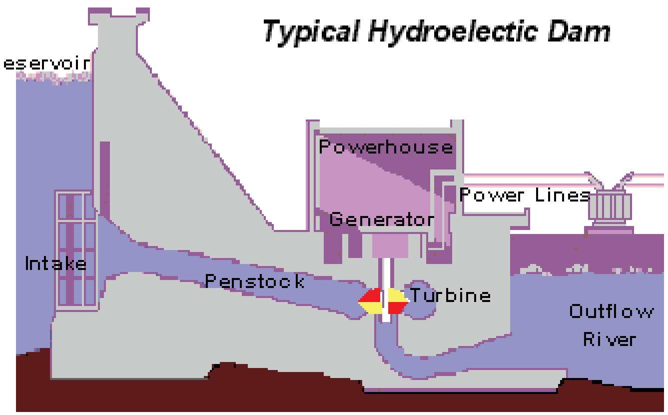
Geothermal	13
Total	7229

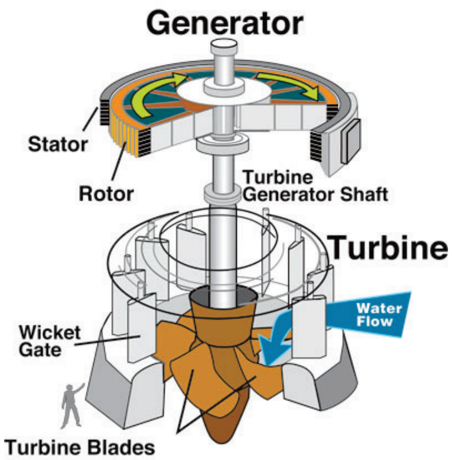
Olah *et al.*, *Beyond Oil and Gas: The Methanol Economy*, 2009.

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 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.

– **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

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

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

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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
  - Was designed to provide 10% of China's electricity demand

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

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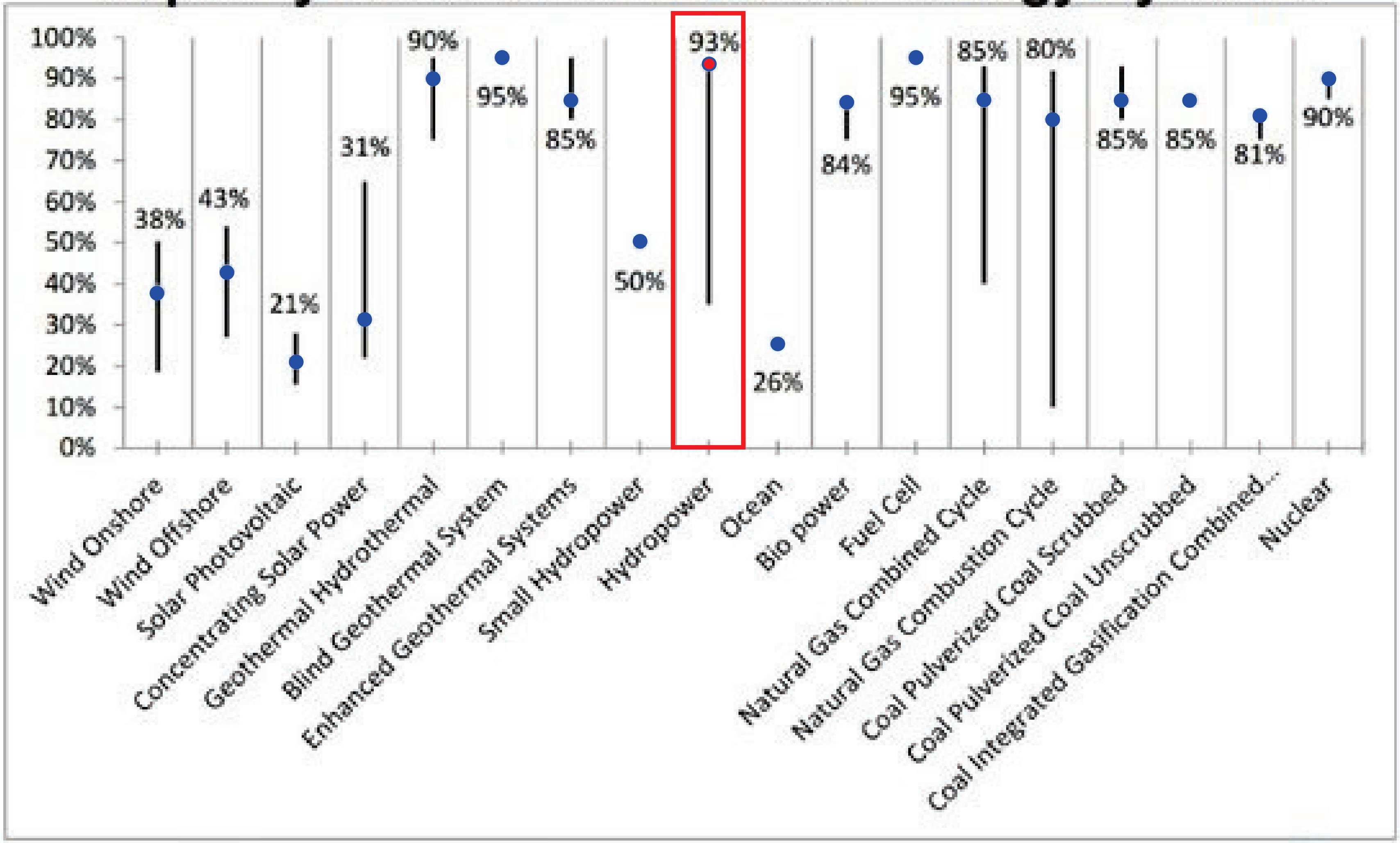
  - Largest construction project in China since Great Wall
  - 1 million people displaced
  - In 2011, provided ~1.7% of China's electricity demand

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

Capacity Factors for Assorted Energy Systems



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

GEOTHERMAL ENERGY ASSOCIATION

https://www.pinterest.com/pin/4292562121285998

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
2009	26	79.470
2010	26	84.370
2011	29	78.290
2012	32	98.100
2013	32	83.270
2014	32	98.800
2015	32	87.000
2016	32	93.500
2017	32	97.600
2018	32	101.600
2019	32	96.880

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

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2019	32	96.880

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

If Three Gorges could run at full capacity for 24/365:

22,500 MW $\times$ 8760 hr = 1.97 $\times$ 10^8 MWh =

1.97 $\times$ 10^8 MWh $\times$ TWh/(10^6 MWh) =

197 TWh output per year

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

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If Three Gorges could run at full capacity for 24/365:
22,500 MW × 8760 hr = 1.97 × 10^8 MWh =
1.97 × 10^8 MWh × TWh/(10^6 MWh) =
197 TWh output per year

Mean output for years with all 32 units = 94.6 TWh

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

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
2009	26	79.470
2010	26	84.370
2011	29	78.290
2012	32	98.100
2013	32	83.270
2014	32	98.800
2015	32	87.000
2016	32	93.500
2017	32	97.600
2018	32	101.600
2019	32	96.880

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

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

Capacity Factor =
94.6 TWh / (197 TWh) = 0.48

Mean output for years with all 32 units = 94.6 TWh

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

Hydro

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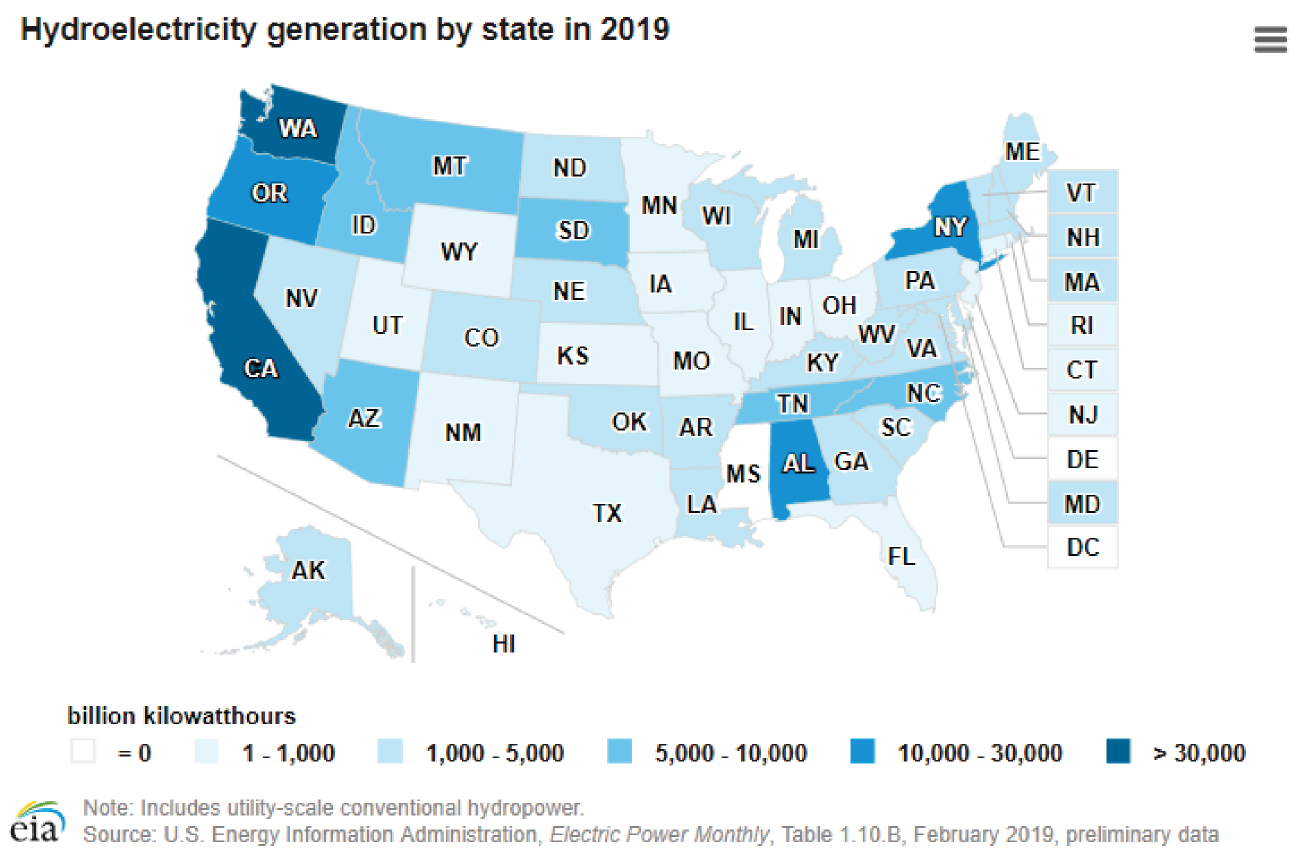
In 2012, the Three Gorges Dam in China took over the #1 spot of the largest hydroelectric dam (in electricity production), replacing Itaipú hydroelectric power plant in Brazil & Paraguay.

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*.

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

Top Hydropower Producing States, 2018

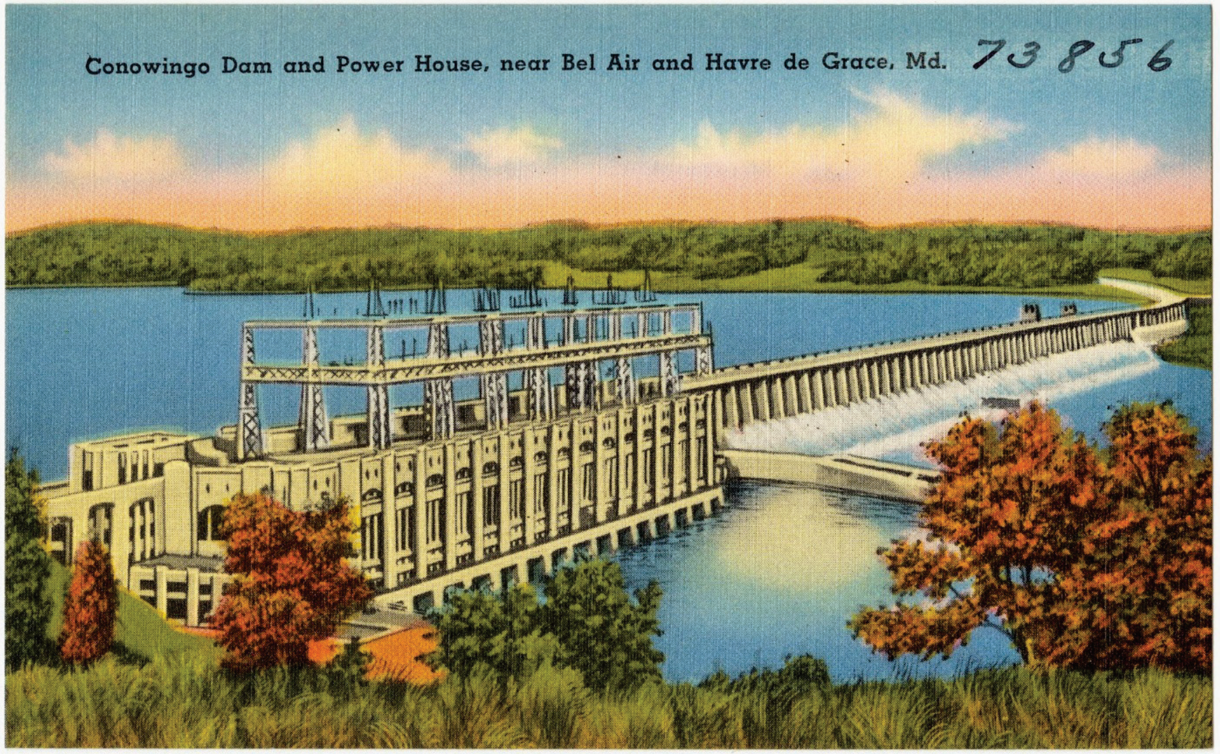


- About half of the total U.S. hydroelectric capacity for electricity generation concentrated in three States (Washington, California, and Oregon)
- ~30% in Washington, location of the largest hydroelectric facility: Grand Coulee Dam.

https://www.eia.gov/energyexplained/hydropower/where-hydropower-is-generated.php

Hydro in Maryland

Hydro in Maryland



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

Location of Conowingo Dam in Maryland

Official name	Conowingo Hydroelectric Station
Country	United States
Location	Cecil and Harford counties, Maryland
Coordinates	39°39′36″N 76°10′26″W
Status	Operational
Construction began	1926 (completed in 1928)
Opening date	1928
Owner(s)	Susquehanna Electric Company
Dam and spillways	
Type of dam	Gravity dam
Impounds	Susquehanna River
Power Station	
Operator(s)	Exelon
Commission date	1928
Type	Run-of-the-river
Turbines	7 x 36 MWe, 4 x 65 MWe
Installed capacity	548 MWe

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:

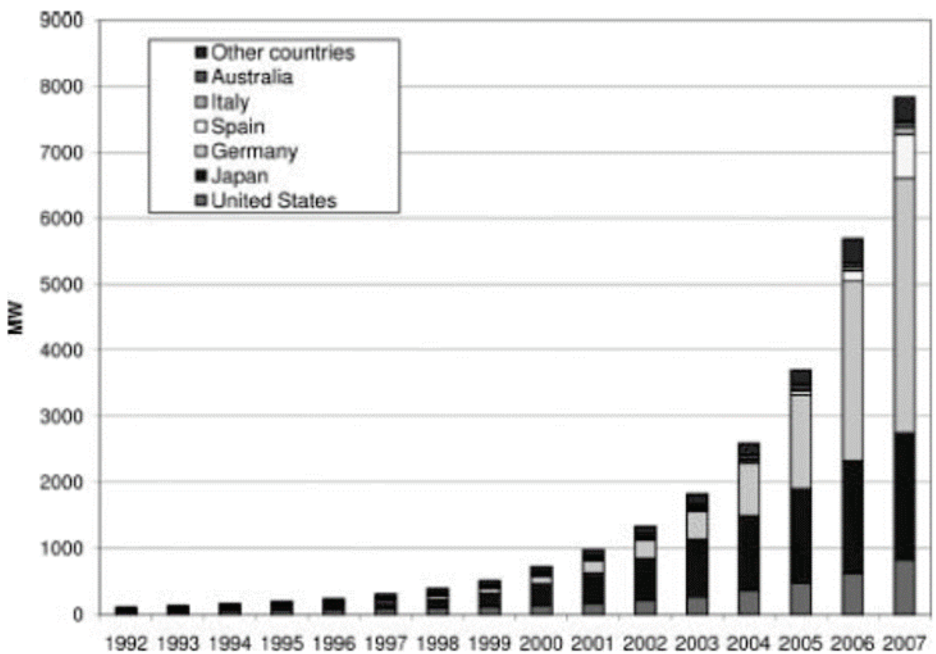


Figure 8.10 Cumulative installed photovoltaic (PV) power in reporting IEA countries. IEA-photovoltaic power systems programme.

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

Solar PV

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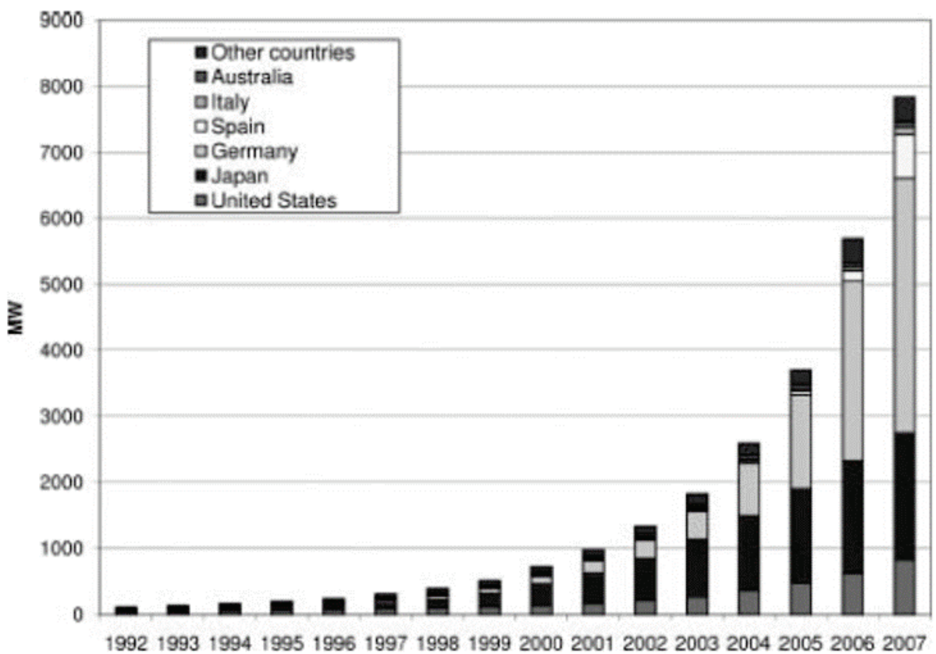

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- PV capacity increased 30% per year from 1997 to 2007:

0.1% of world electricity generation capacity

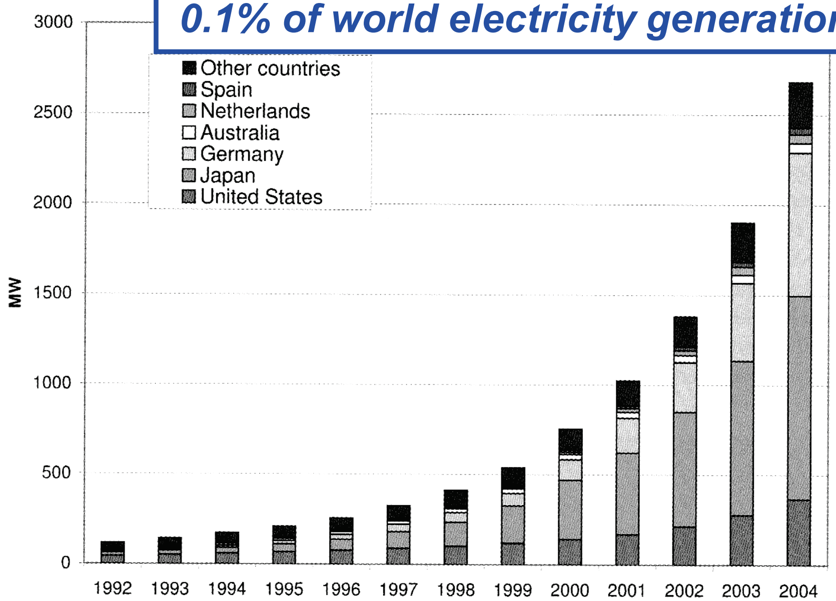


Figure 8.10 Cumulative installed photovoltaic (PV) power in reporting IEA countries. (Source: IEA-Photovoltaic power systems programm

10% of world electricity generation capacity

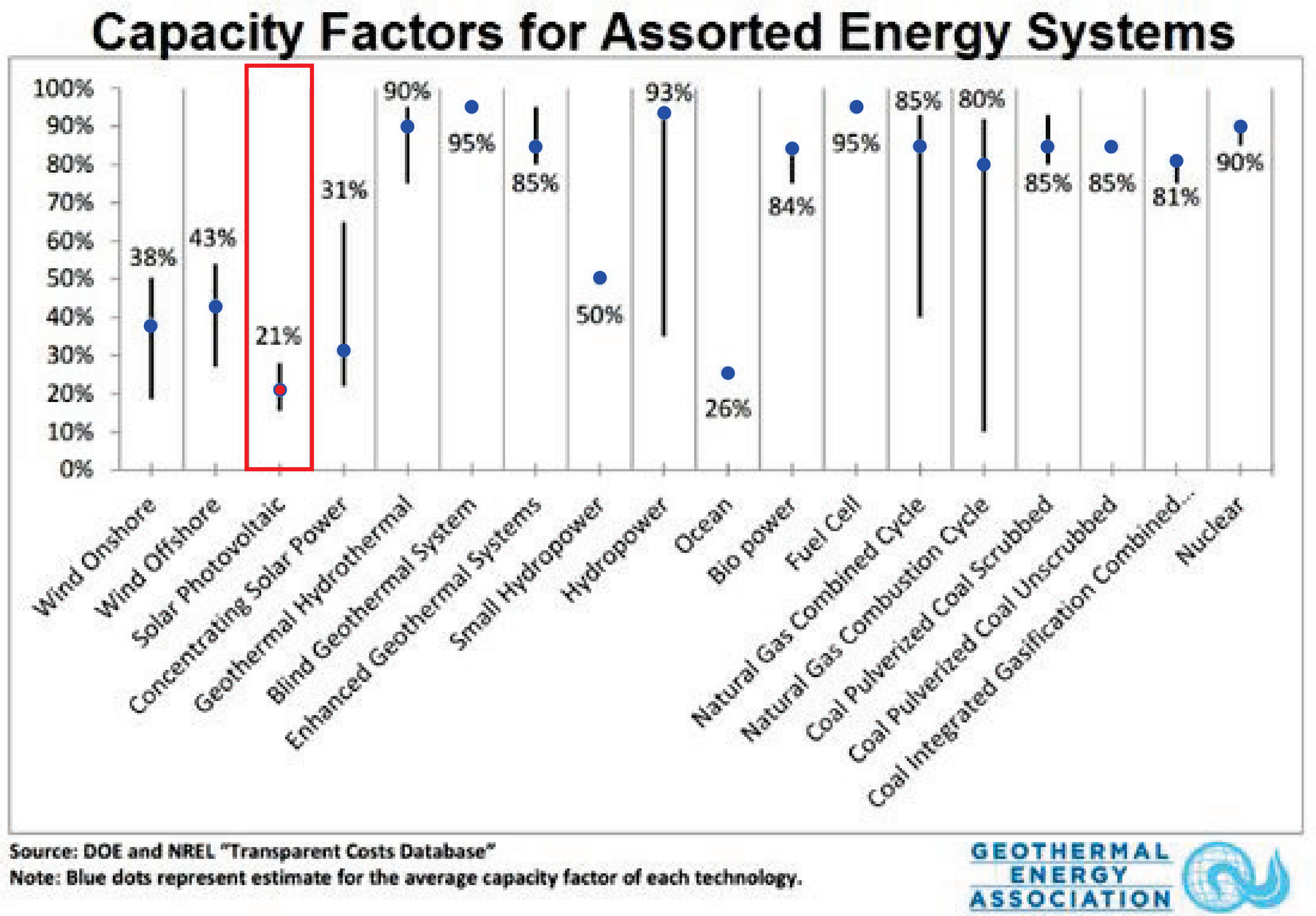
Year	Solar MW
2005	**3,991**
2010	38,260
2015	225,120
2020	**700,490**

Solar

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

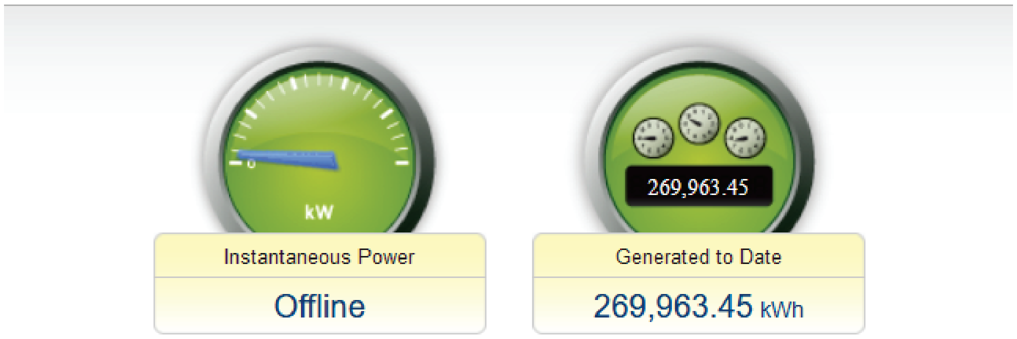
Route 1, just south of Whole Foods, on the opposite side of the road.
22.7 kW system (**power**) has generated 253,242 kW-hours (**energy**) since 22 July 2010

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

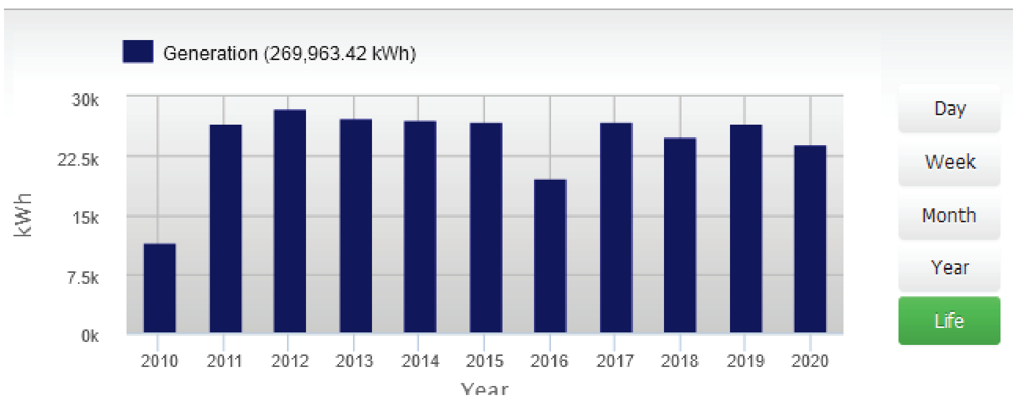


https://www.pinterest.com/pin/429256212128599 8

Solar PV Efficiency



Historical Generation



https://solarnoc.datareadings.com/Client/dashboard/index?F514754962224YDZG5K=_

Operational for:

2010: 205
2011: 365
2012: 366
2013: 365
2014: 365
2015: 365
2016: 366
2017: 365
2018: 365
2019: 365
2020: 327

Total: 3819 days

22.7 kW $\times$ 3819 days $\times$ 24 hrs/day= 2.08 $\times$ 10^6 kW hr

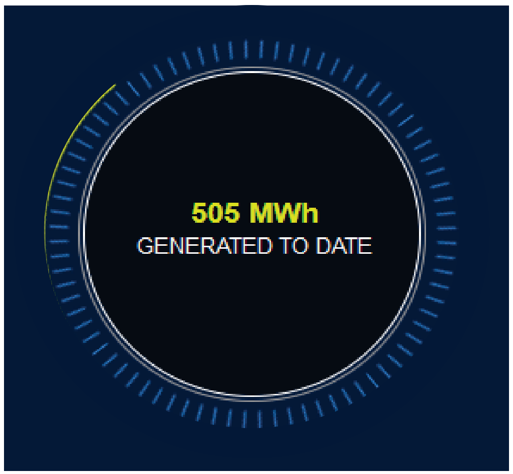
Capacity Factor = 2.70×10^5 kW hr / 2.08×10^6 kW hr = **0.13**

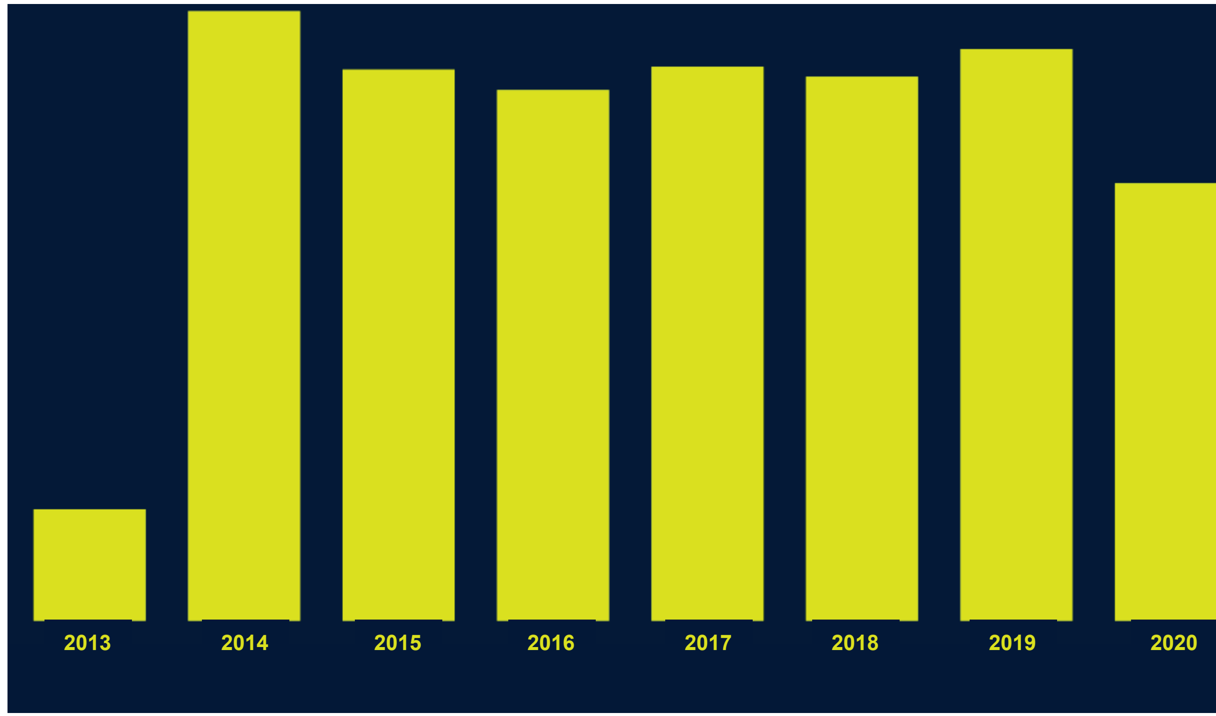
Financial return = 2.70×10^5 kW hr $\times$ 0.13 \$/kW hr = **\$35,100**

Solar: University Park Elementary School

Solar: University Park Elementary School

Capacity Factor





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

64.8 kW $\times$ 2597 days $\times$ 24 hrs/day= 4.04 $\times$ 10^6 kWh

Capacity Factor = {505 MWh $\times$(10^3 kWh / MWh)} / 4.04$\times$$10^6$ kWh = **0.125**

Financial return = 5.05 $\times 10^5$ kW hr $\times$ 0.13 \$/kW hr = **\$65,650**

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.

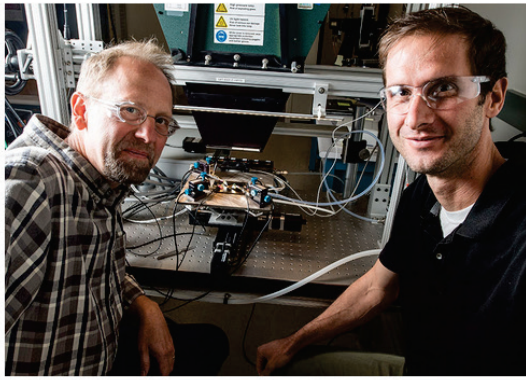
https://en.wikipedia.org/wiki/Shockley–Queisser_limit

Solar PV Efficiency

Six-junction III–V solar cell with 47.1% efficiency

A U.S. research group has developed a new solar cell, based on six active photoactive layers, to capture light from a specific part of the solar spectrum. The scientists claim that they could potentially reach a 50% efficiency rate with the new cell.

APRIL 14, 2020 **EMILIANO BELLINI**



NREL scientists John Geisz (left) and Ryan France.

Researchers from the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) have developed a six-junction III–V solar cell with a 47.1% conversion efficiency rate under 143 Suns concentration.

They said that they have achieved an efficiency rate of 39.2% under one-sun illumination. The cell is based on six different photoactive layers fabricated with alloys of III–V semiconductors, which can each capture light from a specific part of the solar spectrum.

"The device contains about 140 total layers of various III-V materials to support the performance of these junctions, and yet is three times narrower than a human hair," the scientists said.

https://www.pv-magazine.com/2020/04/14/six-junction-iii-v-solar-cell-with-47-1-effiency/

Solar PV Efficiency

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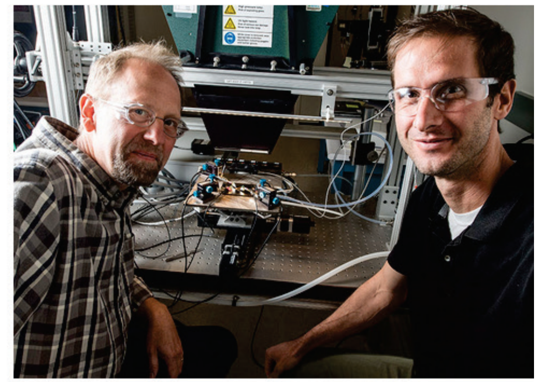

NREL scientists John Geisz (left) and Ryan France.

The cost of producing solar cells based on compounds of III-V element materials – named according to the groups of the periodic table they belong to – has thus far limited such technologies to niche applications, including drones and satellites, where low weight and high efficiency are more pressing concerns than cost.

Share

EMILIANO BELLINI

Emiliano joined pv magazine in March 2017. He has been reporting on solar and renewable energy since 2009.

More articles from Emiliano Bellini

https://www.pv-magazine.com/2020/04/14/six-junction-iii-v-solar-cell-with-47-1-effiency/

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 %

Efficiency Limited By:

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

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Use arrays of cells made of different materials to cover broader spectral range.

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Use mirrors and lenses to focus more light onto cell

Optical losses from shadowing and/or reflection

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Use arrays of cells made of different materials to cover broader spectral range.

Surplus energy transformed into heat

Use mirrors and lenses to focus more light onto cell

Optical losses from shadowing and/or reflection

Structure the surface so reflected light hits another cell

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]

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

Note: 1 GWh = 1000 MWh

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.

Ivanpah

https://www.greenpeace.org/usa/california-can-forge-brighter-future/ivanpah-solar-power-facility-in-california/

Ivanpah

Project capacity: **392 MW** (power = energy / time)

Project output for 2014 to 2019: **3,904,690 MWh** (energy, or power × time)

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

Capacity Factor = 3,904,690 MWh / (392 MW × 8760 h/yr × 6 yrs) = **0.19**

Net electricity production (All) [MWh]

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Sun	NG	Total
2014	10,485	9,630	19,959	24,833	44,784	64,275	35,967	44,070	43,751	56,013	47,177	18,141	**419,085**	**0**	**419,085**
2015	21,888	30,273	57,090	75,304	47,956	77,534	61,681	72,806	66,147	36,971	60,474	44,998	**627,161**	**25,961**	**653,122**
2016	25,439	67,254	58,409	38,449	43,436	65,721	98,849	65,631	82,215	61,312	62,052	34,272	**670,575**	**32,464**	**703,039**
2017	38,305	33,828	50,642	40,589	87,013	97,677	66,664	67,642	75,241	77,805	40,801	43,931	**686,899**	**33,239**	**720,138**
2018	48,873	43,963	59,181	62,060	76,438	115,737	63,197	78,754	91,706	62,396	57,871	35,860	**761,489**	**34,367**	**795,856**
2019	35,211	27,203	48,252	59,345	64,707	101,999	97,520	101,399	72,734	84,848	53,478	25,518	**739,481**	**32,733**	**772,214**
Total													**3,904,690**	**158,764**	**4,063,454**

Ivanpah was advertised as designed to produce 940,000 MWh of electricity per year, based on its nameplate capacity and assumed capacity factor.[81] In its second year of operation, Ivanpah's production of 653,122 MWh of net electricity was 69.5 percent of this value, ramping up from 44.6 percent in the first year. In its fifth year, the annual production was 84.7% of its advertised value.

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

Ivanpah

Output: 392 MW capacity

Could supply all of US electricity needs in 2019
if built over a 176 mile × 176 mile area
Construction cost: ~$48 / kW-hr for one yr's prod

Fossil backup, night time preservation, and morning pre-heating, is provided by natural gas and provides up to 4% 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 85×85 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.*

Are these the same ?!?

85 miles = 136 km

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 136 × 136 km, roughly the size of New Jersey.

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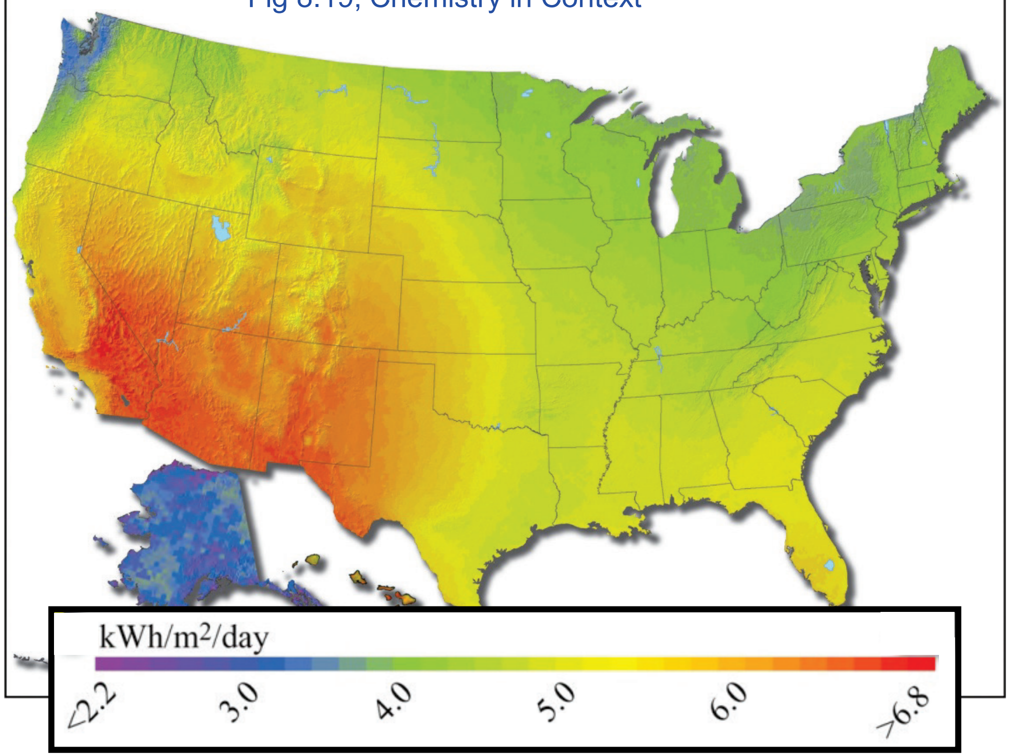
Fig 8.19, Chemistry in Context



Olah et al. state:

On a ***perfectly clear day***, Earth receives about 1000 W m^{-2} at noon

In the US, the highest *daily* solar insolation is about 6000 Wh m^{-2} or 6 kWh m^{-2}

Let's do some math with these numbers

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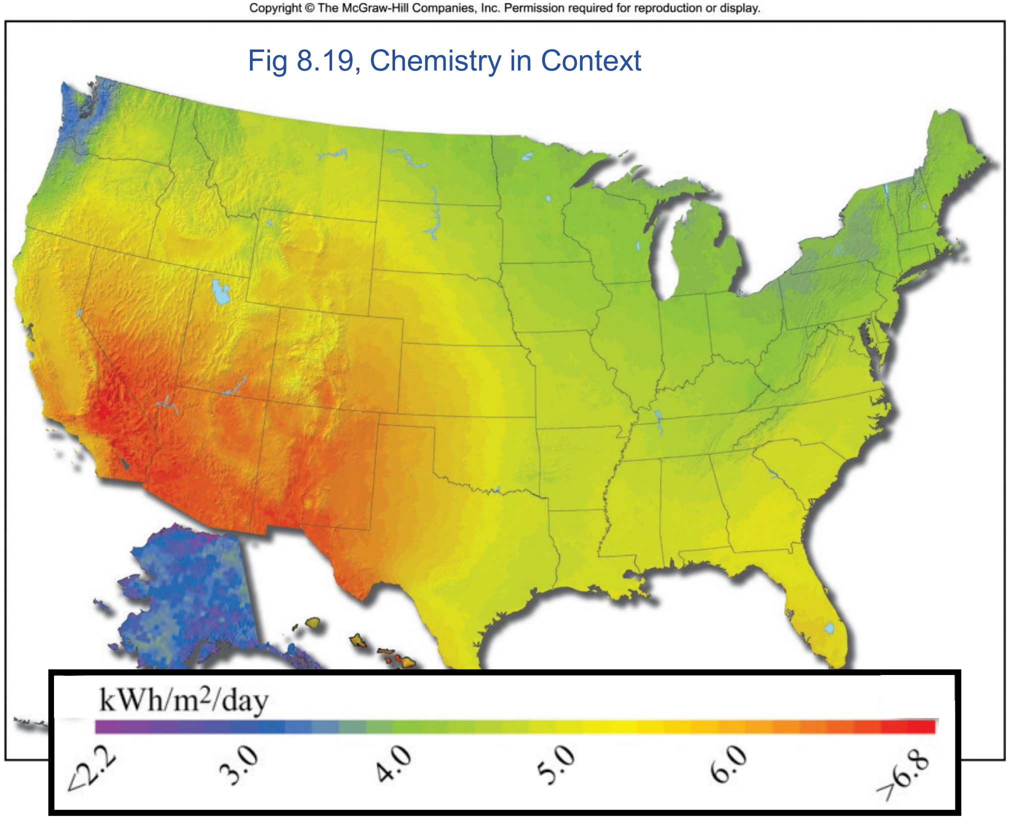

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In the US, the highest *daily* solar insolation is about 6000 Wh m^{-2} or 6 kWh m^{-2}

Let's assume 5 kWh m^{-2}

In 2019, US used 3750×10^6 MWh = 3750×10^9 kWh of electricity

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

Would need an area of:

$\{3750 \times 10^9 \text{ kWh} / (5 \text{ kWh m}^{-2} \times 365)\}^{1/2}$ = 45 km by 45 km

if we could capture the full 5 kWh m^{-2}

Area is 100 km × 100 km with 21% capacity factor

130 km × 130 km with 12.5% " "

Nevada Solar One / US Energy Needs

US Electricity Consumption in 2019 was 3750 TWh or 3750×10^6 MWh

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

Nevada Solar One annual output averaged over past 5 years: 113,000 MWh

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

To meet U.S. Energy Needs, would need an area of:

$(3750 \times 10^6$ MWh / 113,000 MWh$) \times 0.6$ square mile $= 2 \times 10^4$ square miles

$[2 \times 10^4$ square miles$]^{1/2}$ = 141 by 141 miles = 226 km by 226 km

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Cost: $\$2 / \text{KWh} \times 3750 \text{ TWh} \times (10^9 \text{ KW/TW}) = \$\, 7.5 \times 10^{12}$ or **$7.5 trillion dollars**

US GDP in 2019 was **$21.4 trillion dollars**

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Cost: \$2 / KWh × 3750 TWh × (10^9 KW/TW) = \$ 7.5×10^{12} or **\$7.5 trillion dollars**

US GDP in 2019 was **\$21.4 trillion dollars**

35% of GDP is considered for a single year;

Nevada Solar One / US Energy Needs

US Electricity Consumption in 2019 was 3750 TWh or 3750 $\times$ 10^6 MWh

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

Nevada Solar One annual output averaged over past 5 years: 113,000 MWh

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

To meet U.S. Energy Needs, would need an area of:
(3750 $\times$ 10^6 MWh / 113,000 MWh) $\times$ 0.6 square mile = 2 $\times$ 10^4 square miles

[2 $\times$ 10^4 square miles]$^{1/2}$ = 141 by 141 miles = 226 km by 226 km

Cost: \$2 / KWh $\times$ 3750 TWh $\times$ (10^9 KW/TW) = \$ 7.5 $\times 10^{12}$ or **\$7.5 trillion dollars**

US GDP in 2019 was **\$21.4 trillion dollars**

35% of GDP is considered for a single year;
~ 1% of GDP if spread out over 30 years time

Wind

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

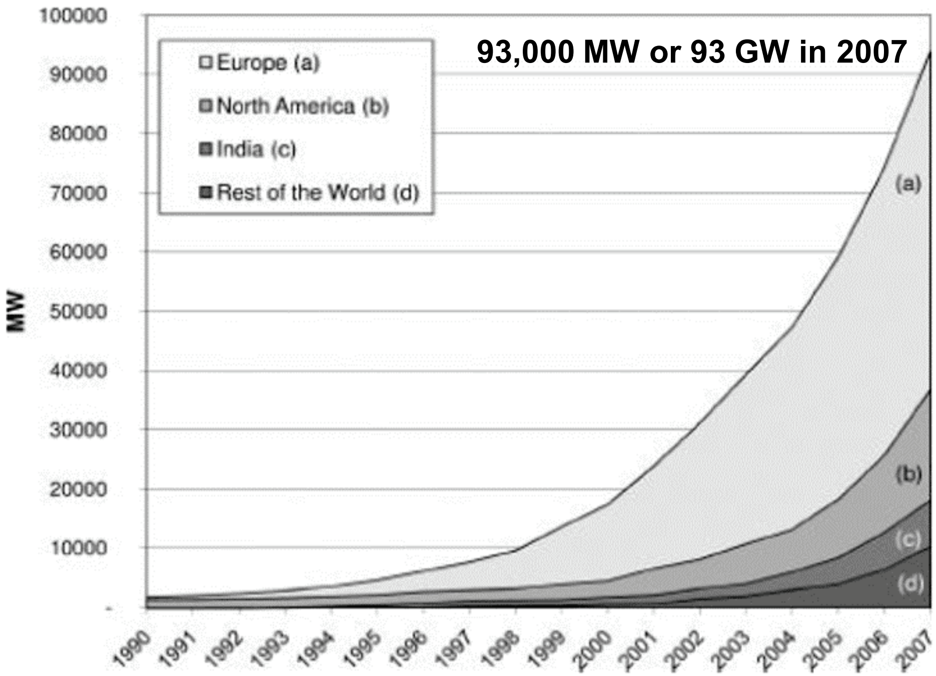


Figure 8.8 World wind power installed capacity. (Source: Global Wind Energy Council, European Wind Energy Association, IEA.)

Total Source	GW (year 2020)
Coal	2154
Natural Gas	1662
Hydro-electric	1262
Solar	700
Wind	**646**
Nuclear	374
Liquid Fossil Fuel	297
Other Renewable (Biomass)	121
Geothermal	13
Total	7229

- 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 9% 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

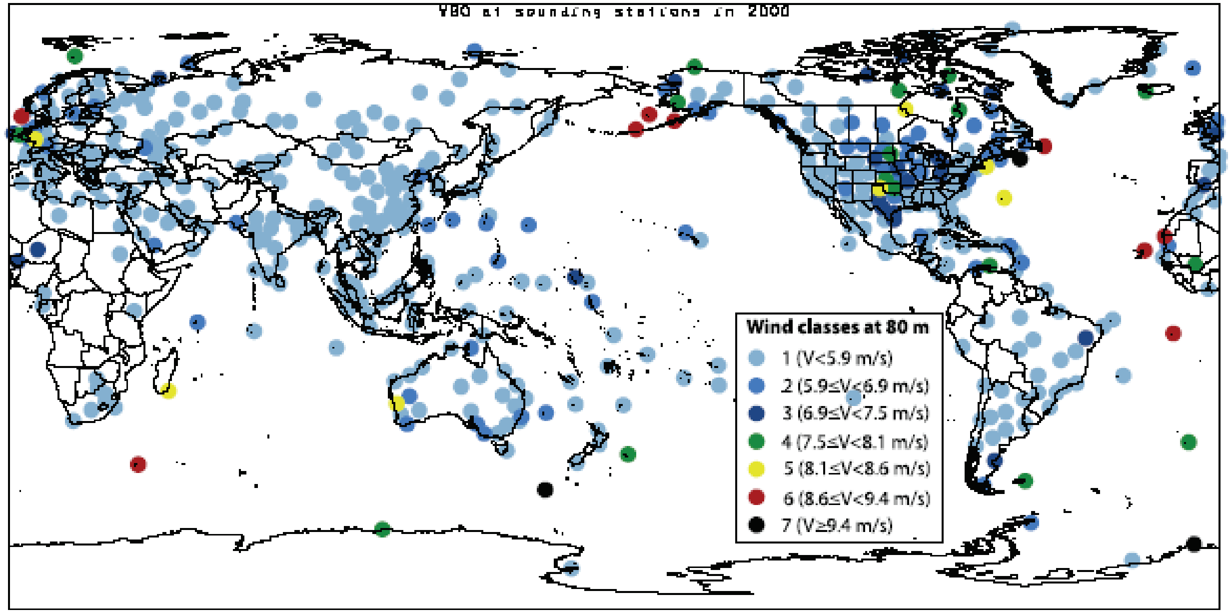


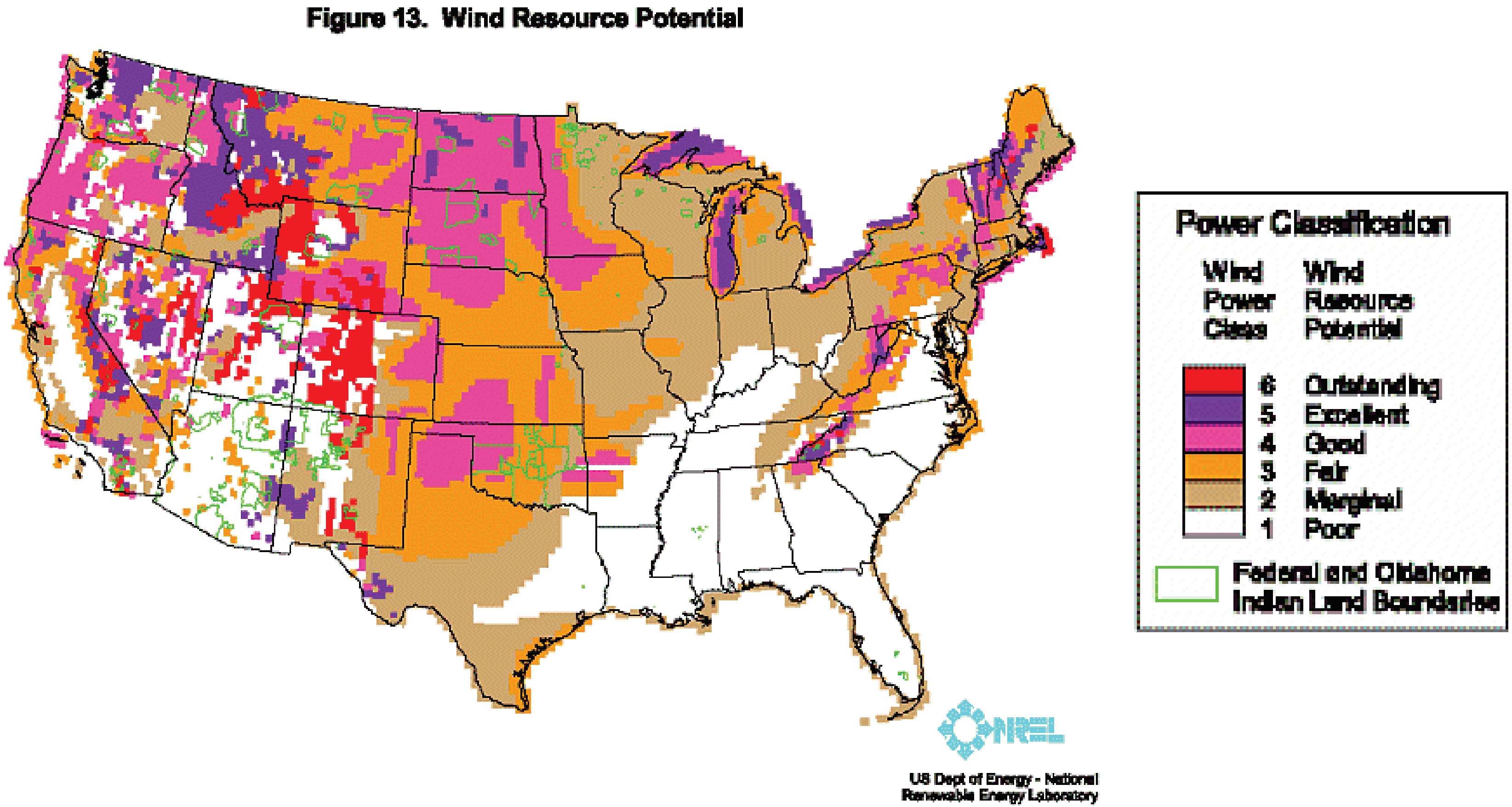
Figure 2. Map of wind speed extrapolated to 80 m and averaged over all days of the year 2000 at sounding locations with 20 or more valid readings for the year 2000.

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

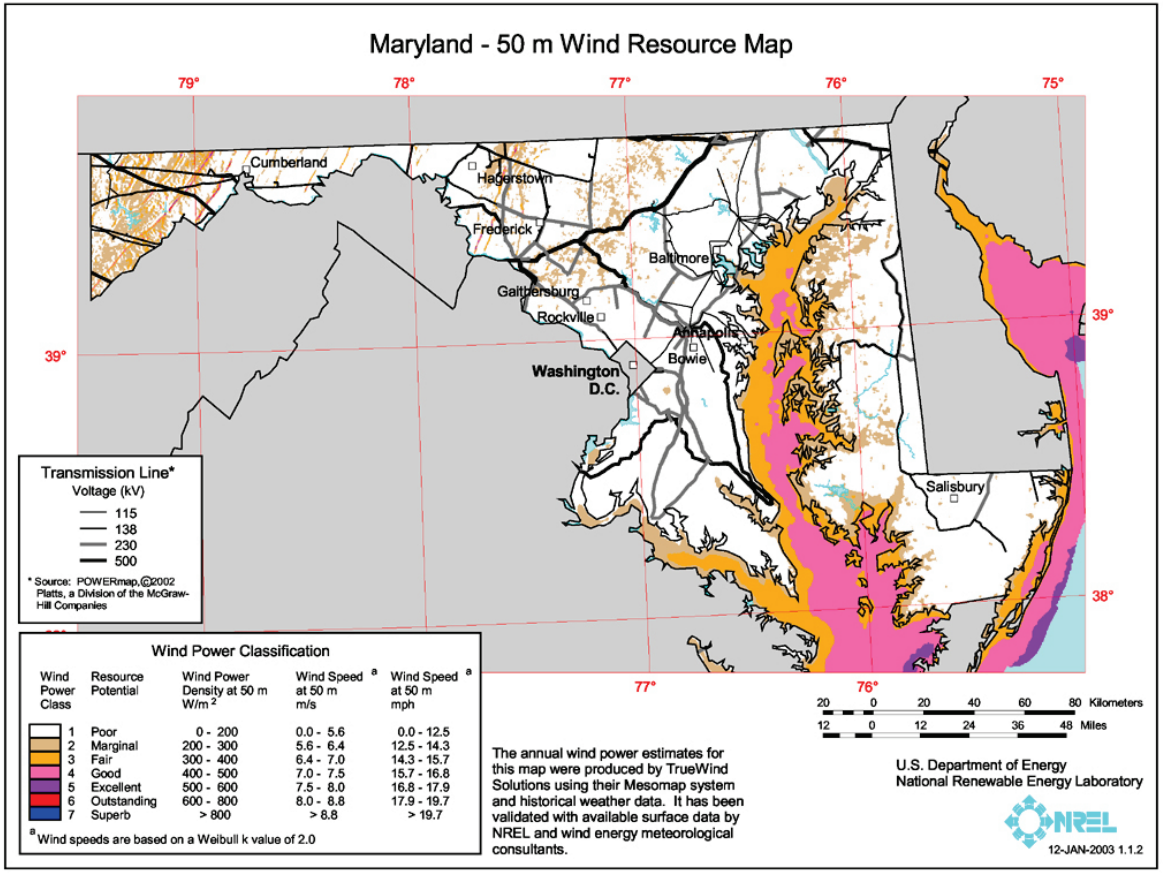
Wind

- 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



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

Wind

Samsø, Denmark

- 40 square miles
- 4000 inhabitants
- wind power, on-shore and off-shore, key components of world's first ***carbon neutral community***

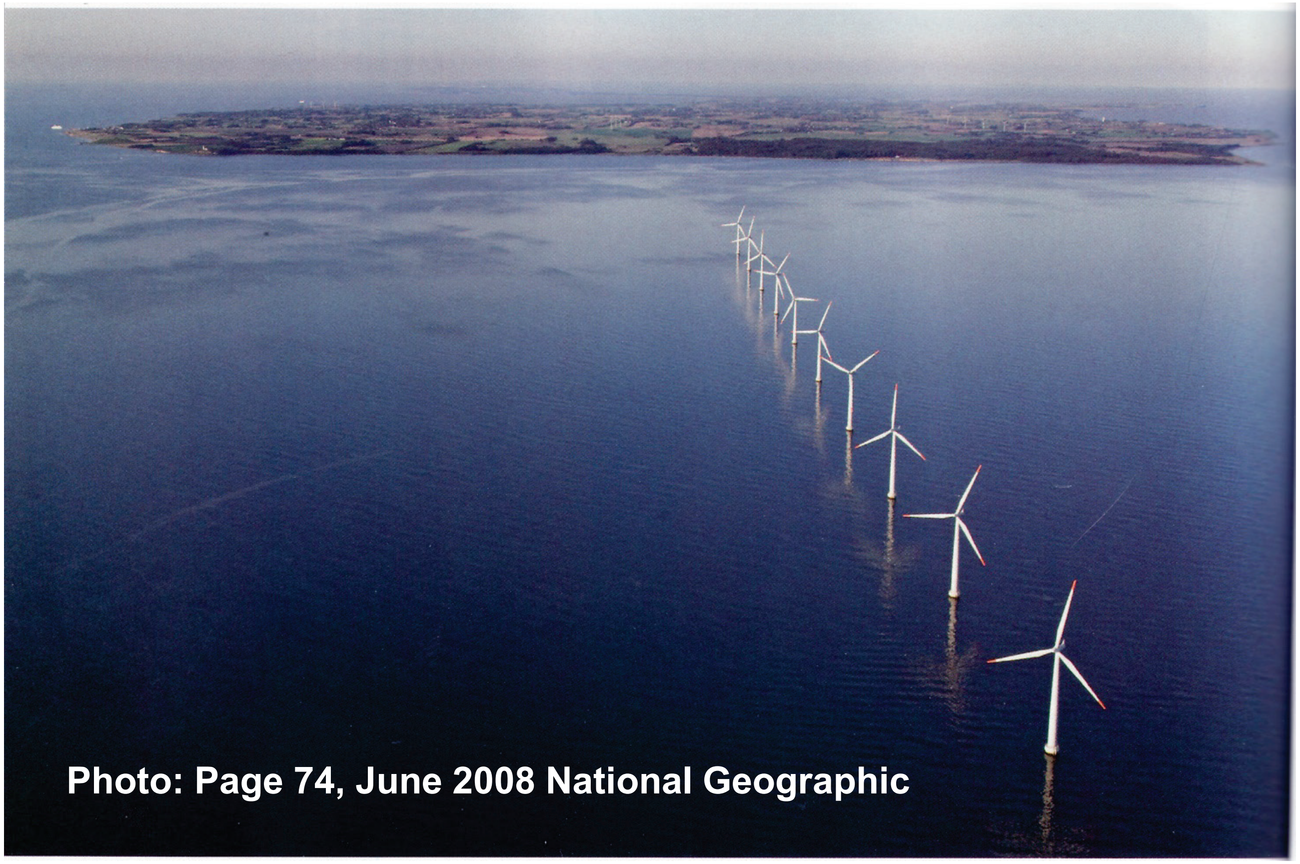


Photo: Page 74, June 2008 National Geographic

http://www.cbsnews.com/stories/2007/03/08/eveningnews/main2549273.shtml?source=RSSattr=SciTech_2549273

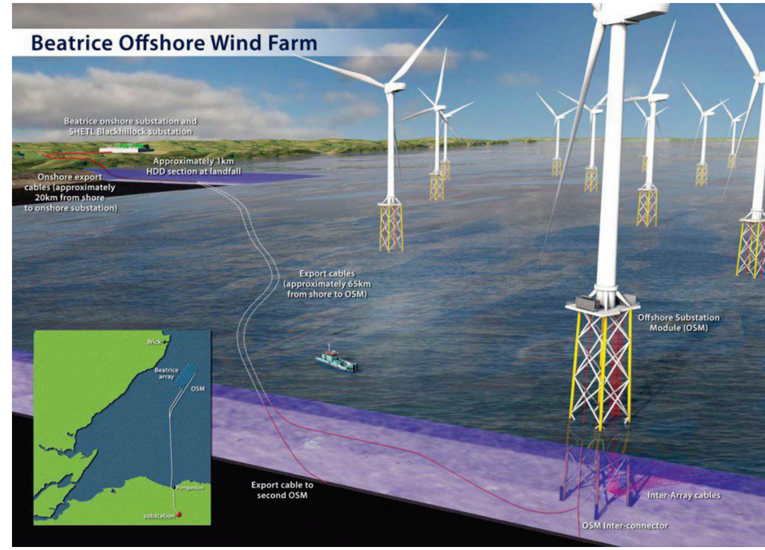
http://inapcache.boston.com/universal/site_graphics/blogs/bigpicture/earthday_04_23/e22_19972095.jpg

Offshore Wind, Scotland

List of countries by cumulative installed offshore wind power capacity (MW)[2]

Rank	Country	2016	2017	2018
1	United Kingdom	5,156	6,651	7,963
2	Germany	4,108	5,411	6,380
3	China	1,627	2,788	4,588
4	Denmark	1,271	1,268	1,329
5	Belgium	712	877	1,186
6	Netherlands	1,118	1,118	1,118
7	Sweden	202	202	192
8	Vietnam	99	99	99
9	South Korea	35	38	73
10	Finland	32	92	87
11	Japan	60	65	65
12	United States	30	30	30

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



http://www.scottishconstructionnow.com/wp-content/uploads/sites/11/2016/06/Beatrice-offshore-wind-farm.jpg
https://www.offshorewindindustry.com/sites/default/files/field/image/offshoreb_beatrice_offshore_wind_farm.jpg

Offshore Wind, Scotland

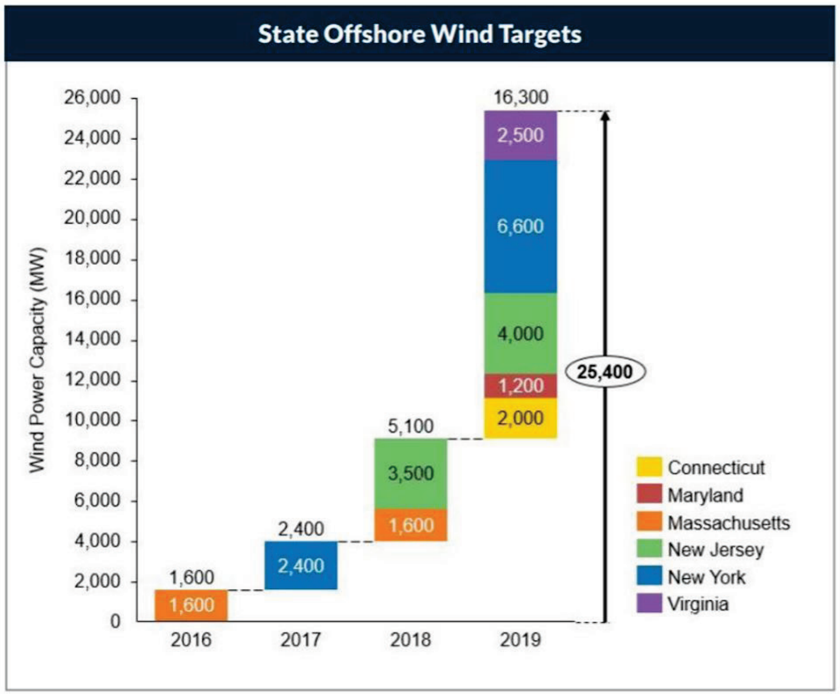
https://www.youtube.com/watch?v=1vy1ajBe8mY

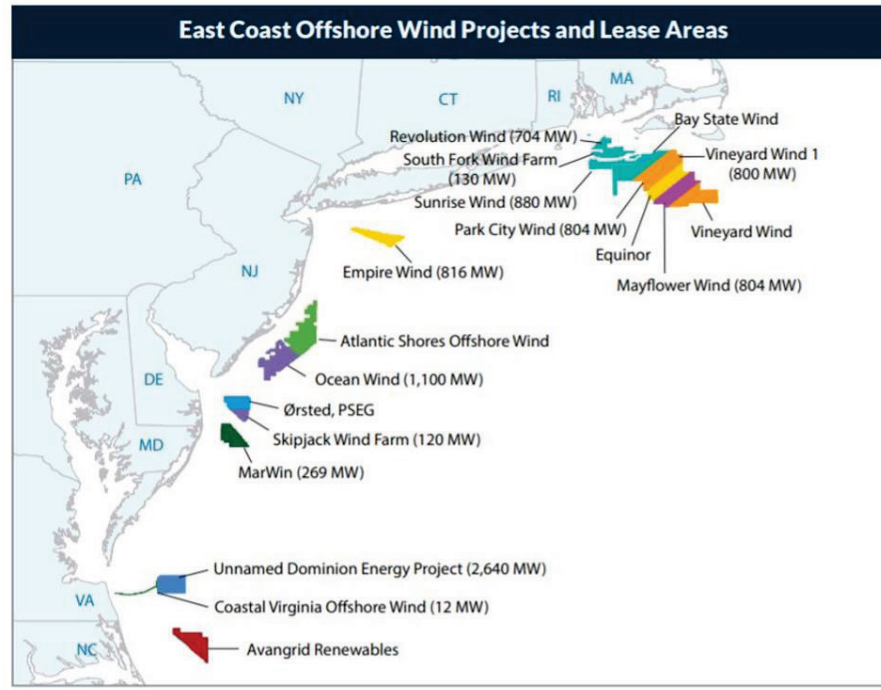
Offshore Wind, U.S.

Mar 24, 2020, 07:30am EDT

Four Federal Policies Could Help Offshore Wind Jump Start Our Coronavirus Economic Recovery

Silvio Marcacci Contributor





https://www.forbes.com/sites/energyinnovation/2020/03/24/these-federal-policies-could-help-offshore-wind-jump-start-americas-economic-recovery/#132693e578cc

Rest of Material Is "Back-up"

Geothermal

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

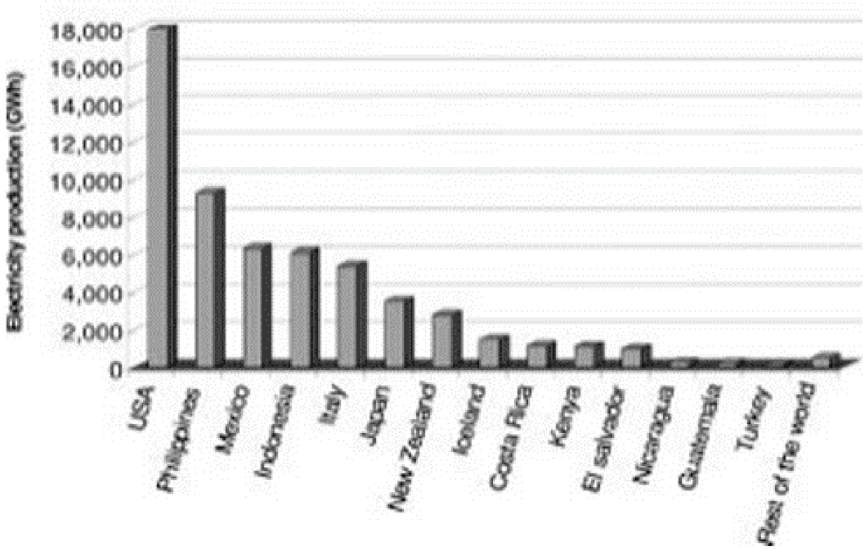


Figure 8.5 Geothermal electricity production, 2005. (Source: Bertani, R. [103].)

• 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:

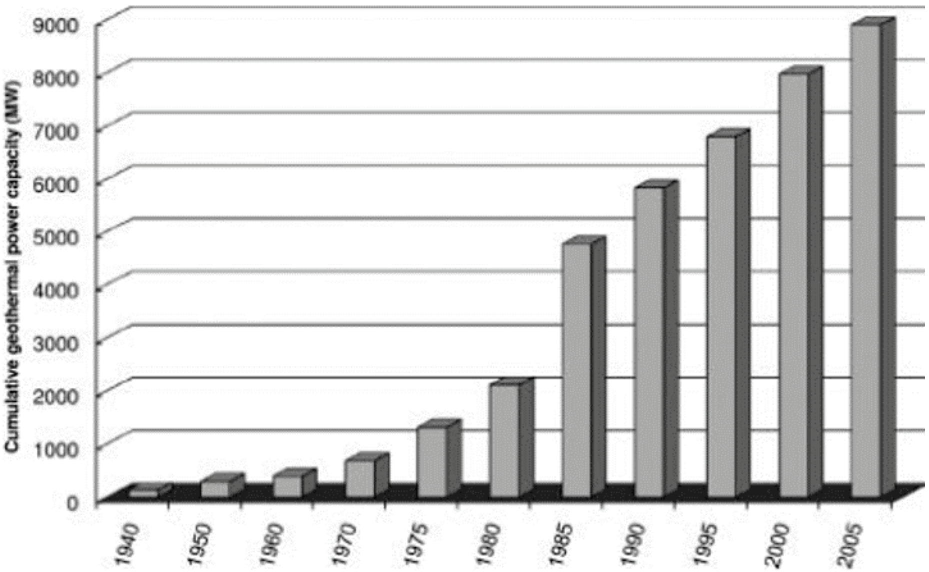


Figure 8.6 Worldwide development of geothermal electric power.

Total Source	GW (year 2020)
Coal	2154
Natural Gas	1662
Hydro-electric	1262
Solar	700
Wind	646
Liquid Fossil Fuel	297
Nuclear	259
Other Renewable (Biomass)	121
Geothermal	**13**
Total	7114

but total production capacity, about **13 GW in 2020**, represents only 0.2% 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?

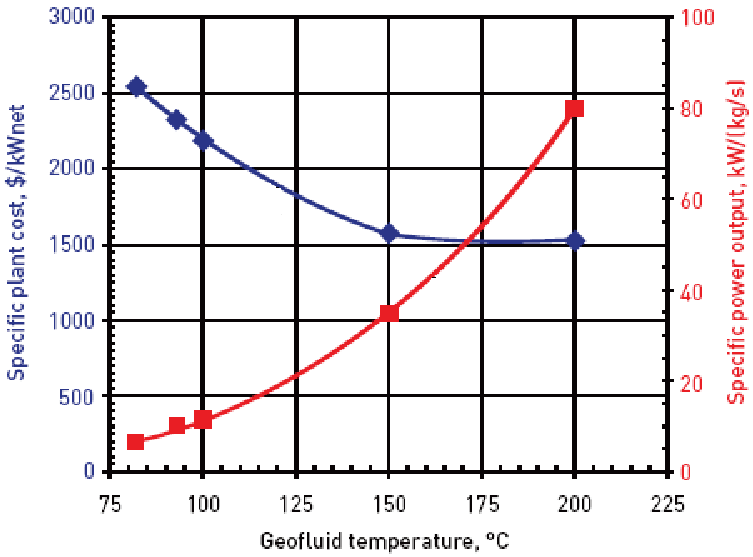
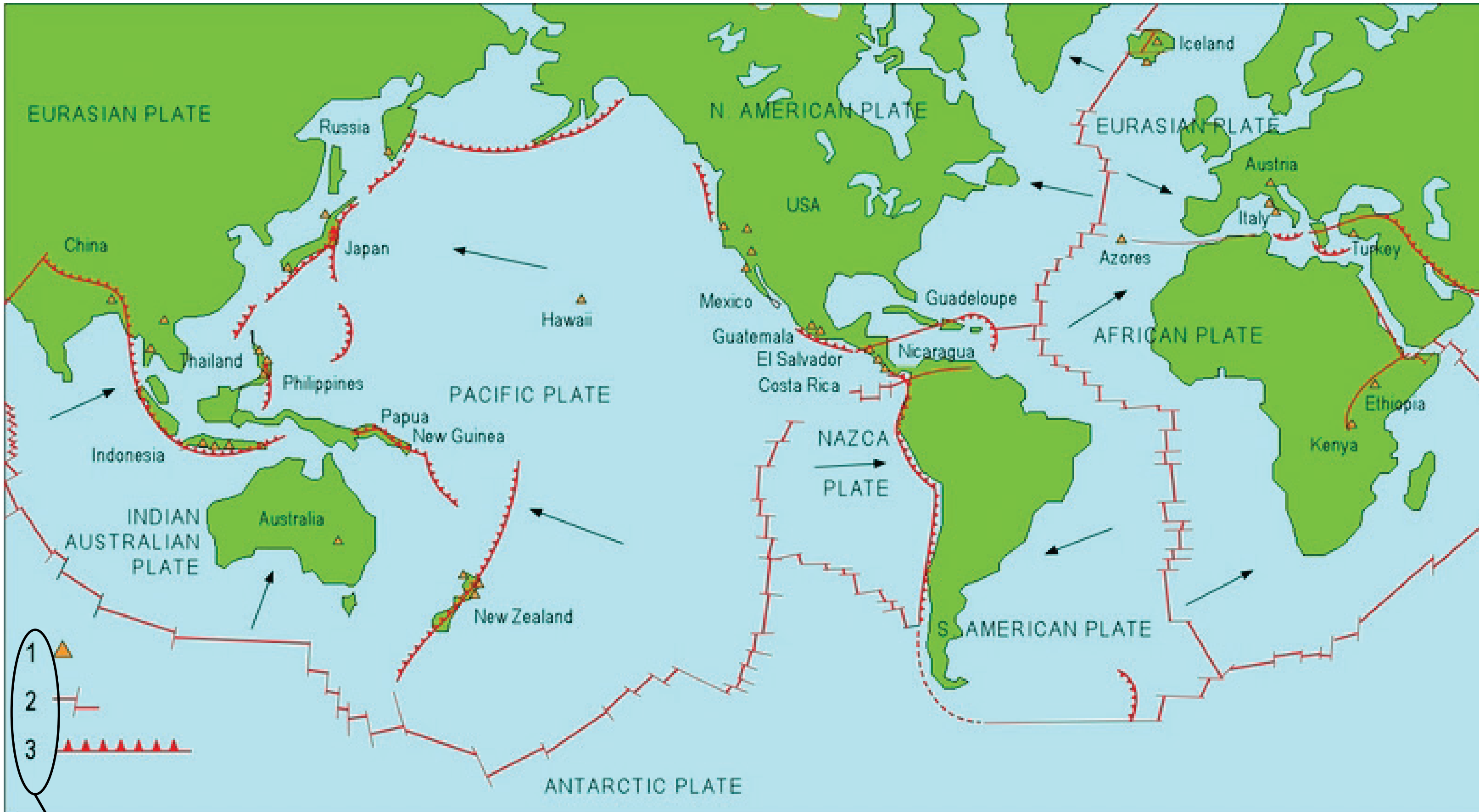


Figure 7.4 Cost and performance of 1 MW binary power plants as a function of geofluid temperature in degrees Celsius (°C).

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

Top Energy NZ - Ngāwhā Geothermal Power Station Expansion update - MARCH 2019

https://www.youtube.com/watch?v=dFLX6oySYcc

Geothermal

- Temperature of source critical:
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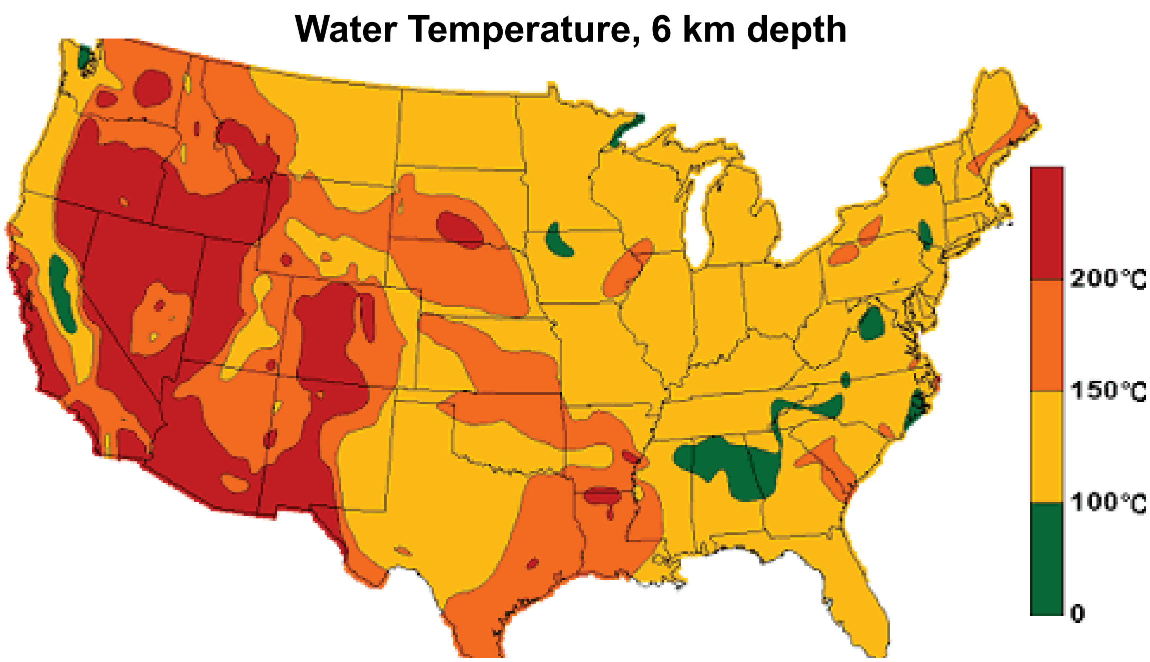
Map of U.S. Water Temperature



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

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

Power (Energy/Time)

Total Source	GW (year 2020)
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Source: https://www.eia.gov/outlooks/ieo/tables_ref.php

In 2020, **43%** of global electricity generating capacity does not release prodigious GHGs to the atmosphere

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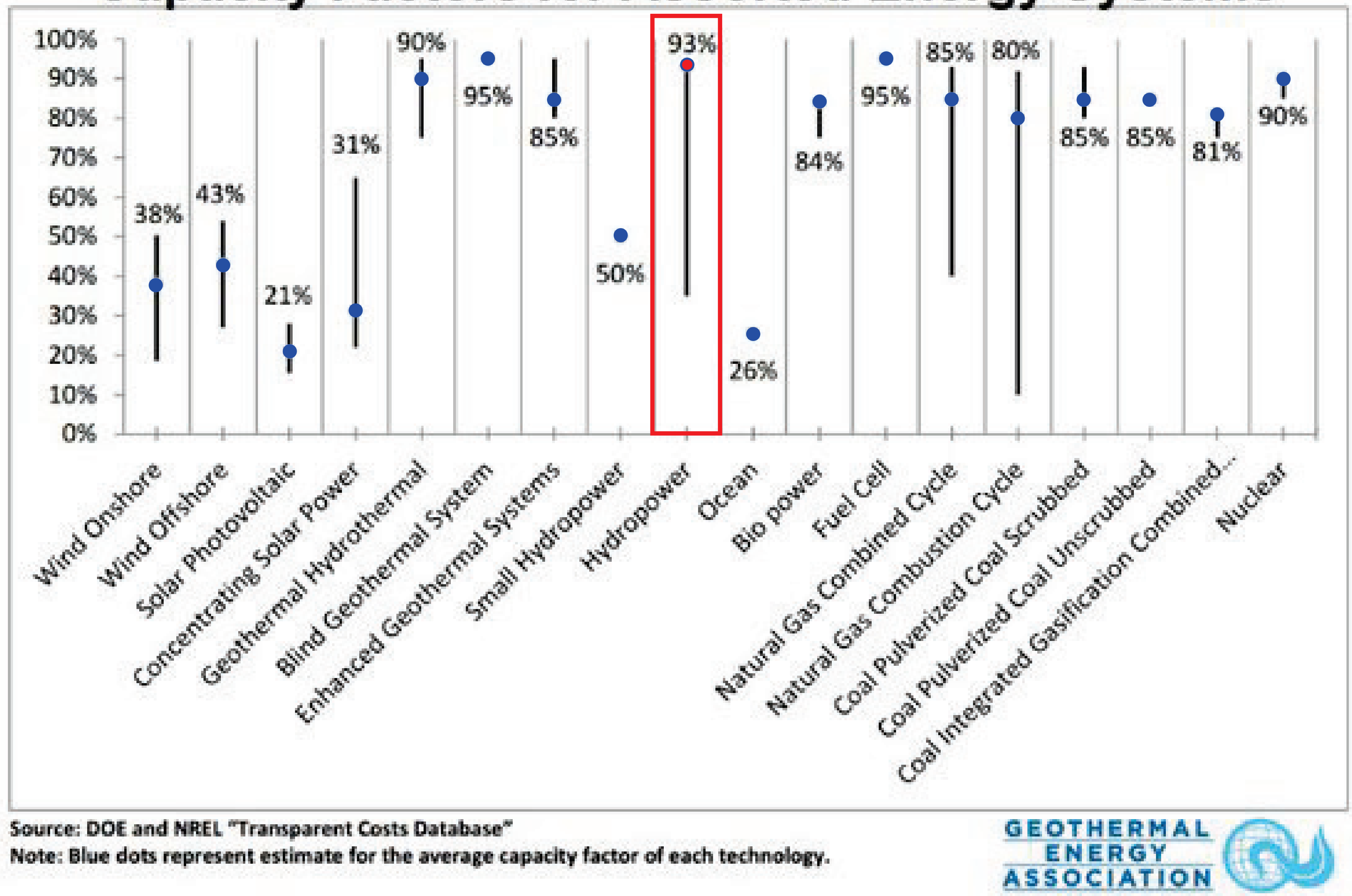
In 2020, **43%** of global electricity generating capacity does not release prodigious GHGs to the atmosphere

Capacity Factors for Assorted Energy Systems



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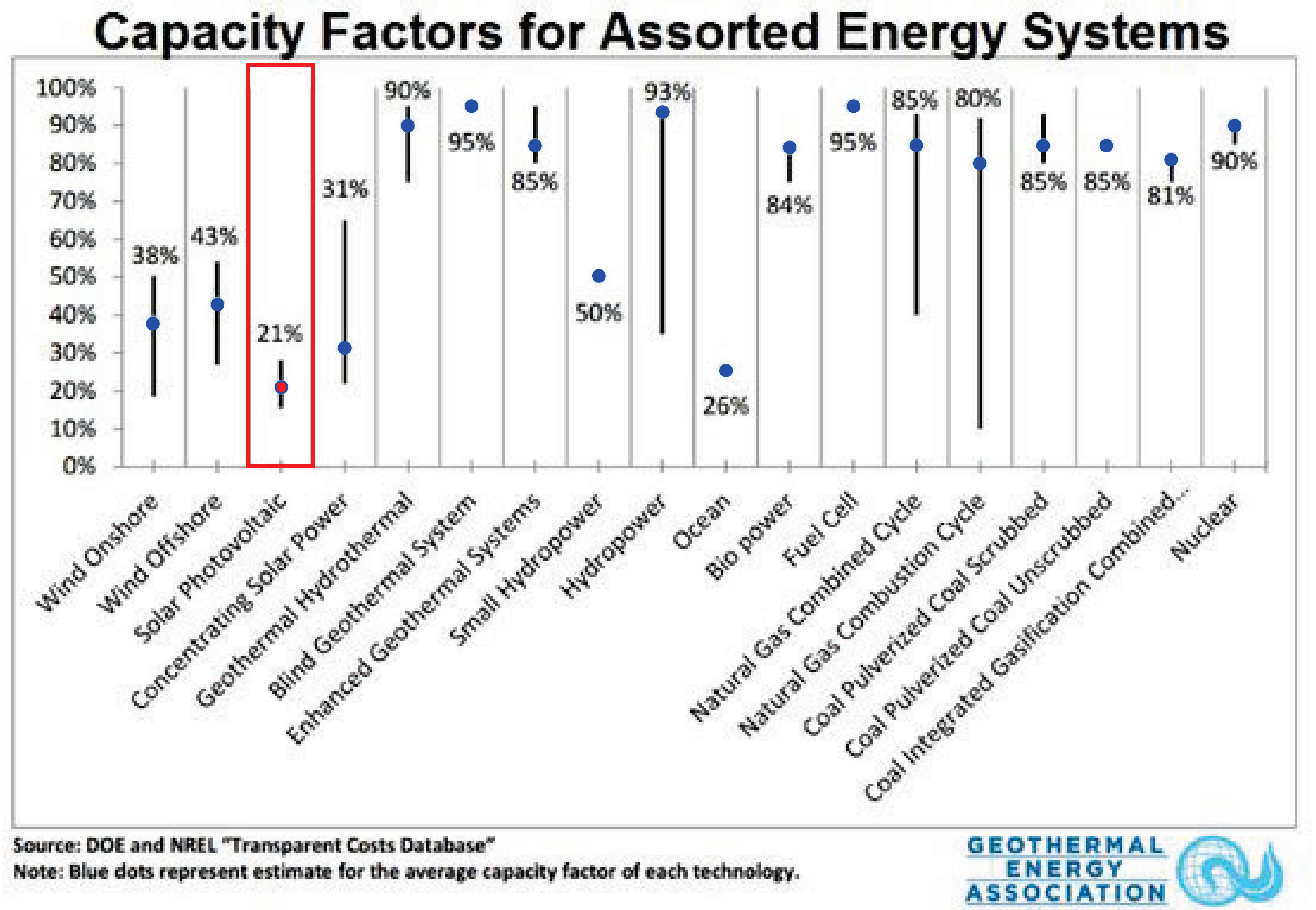

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