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

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 Catch-Up

30 November 2020

Announcement

Students might be interested in watching *Planet of the Humans* by Jeff Gibbs and Michael Moore, released 21 April 2020, at https://planetofthehumans.com

In my opinion this film, an expose mainly focused on energy from the combustion of biomass, solar, wind, and corporate greed, gets many points “right” and certain other important points “wrong”.

https://twitter.com/LibSnoflake/status/1252652168991121411

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.

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Output averaged about 113 MWh over past 5 years

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

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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

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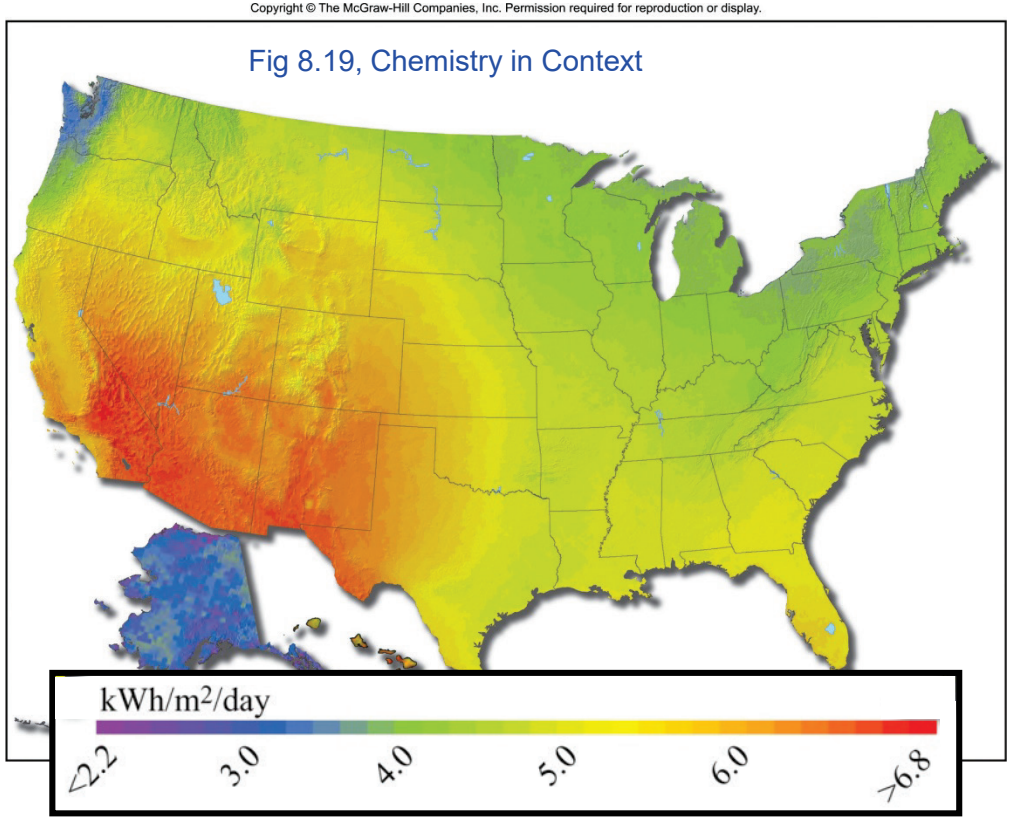
Fig 8.19, Chemistry in Context



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

Solar Energy

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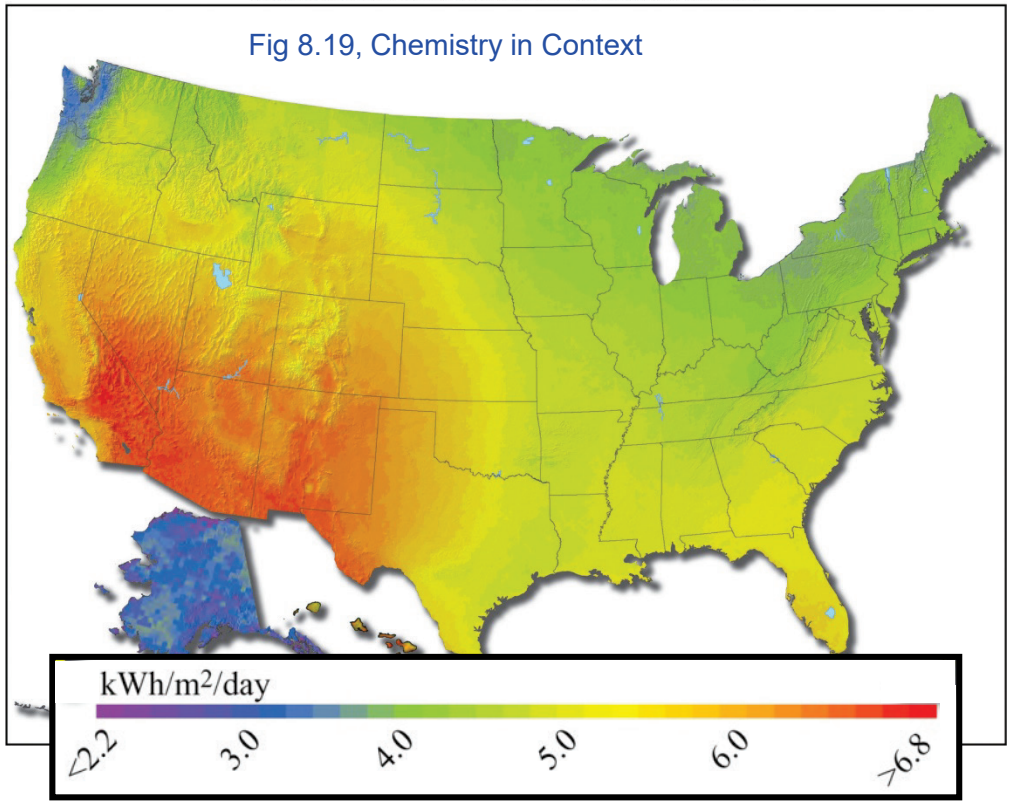

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Let's assume 5 kWh m^{-2}

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:

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

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

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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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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

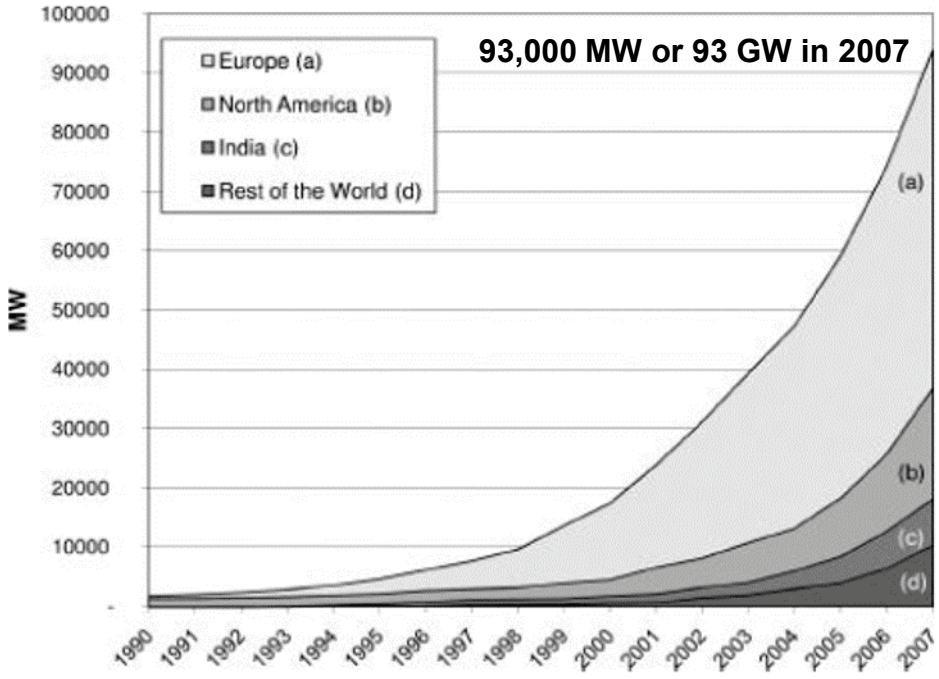

Figure 8.8 World wind power installed capacity. (Source: Global Wind Energy Council, European Wind Energy Association, IEA.)

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

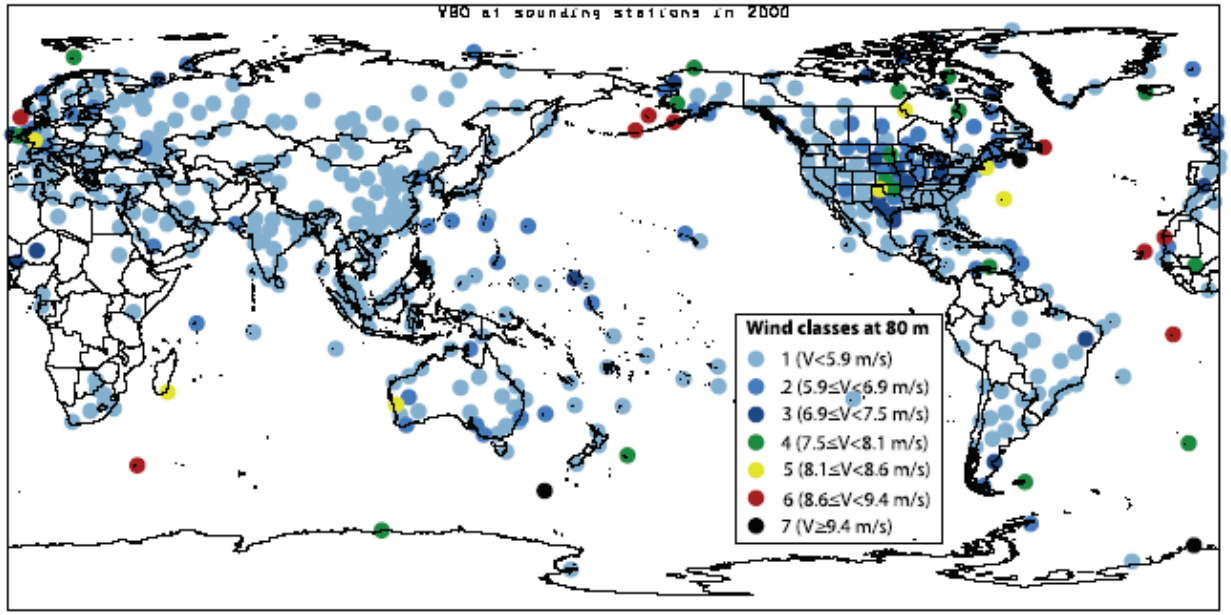

Figure 2. Map of wind speed extrapolated to 80 m and averaged over all days of the year 2000 at sounding locations with 20 or more valid readings for the year 2000.

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
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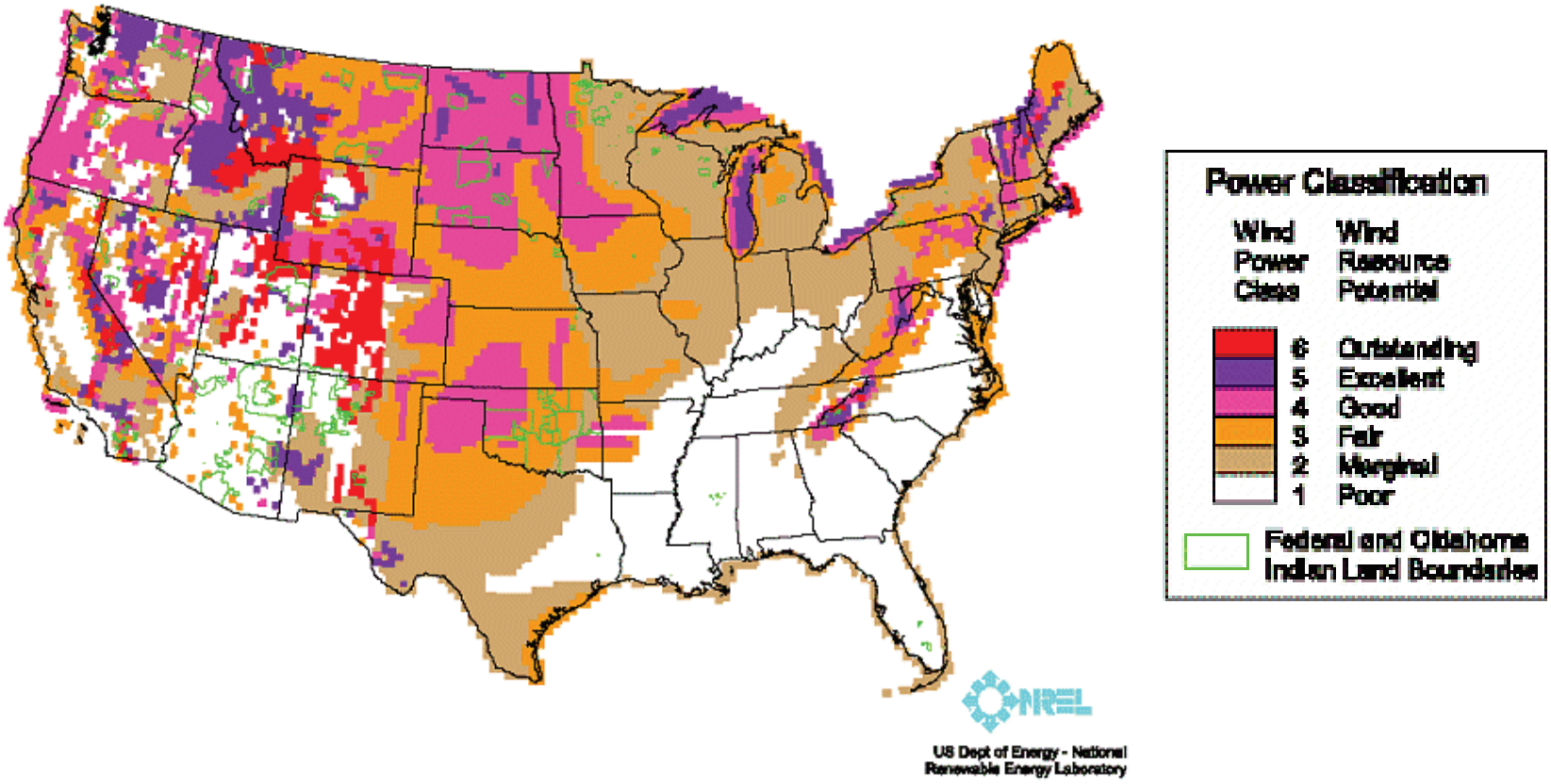
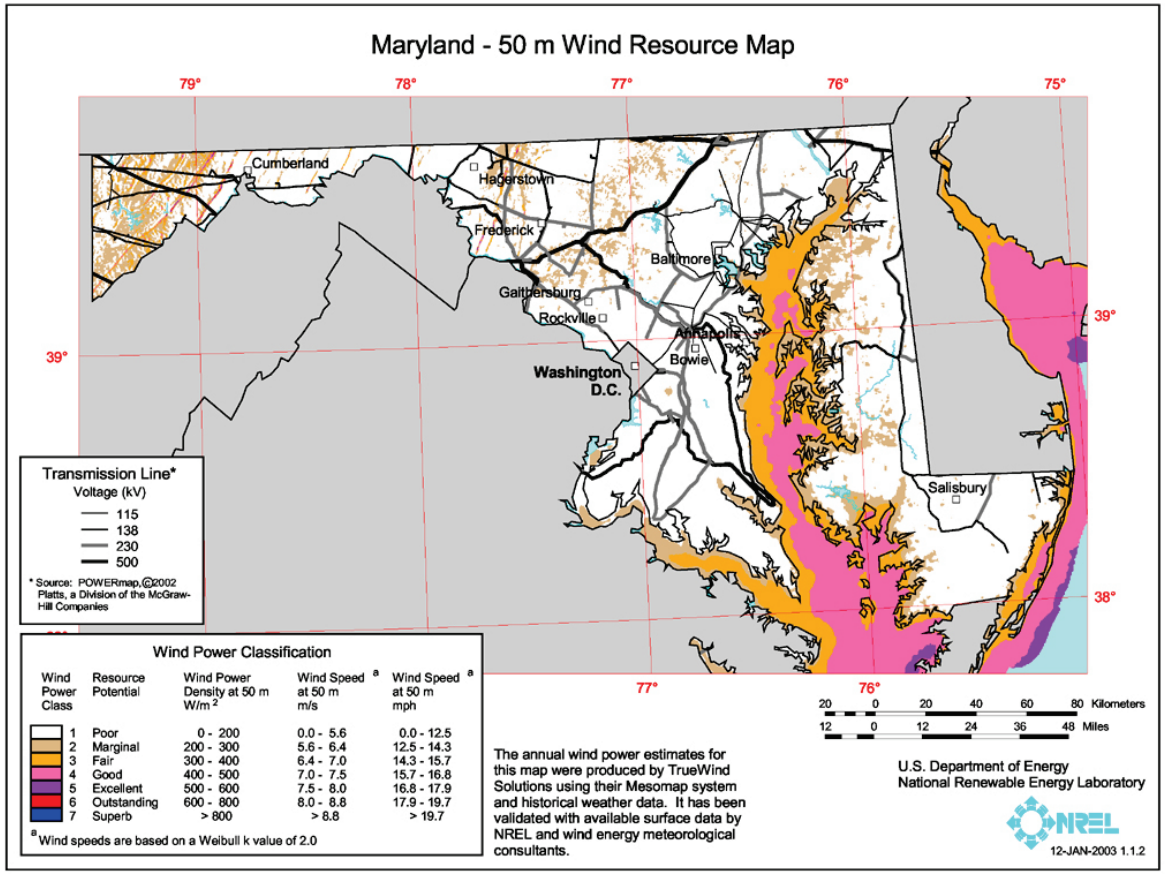
Figure 13. Wind Resource Potential



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:

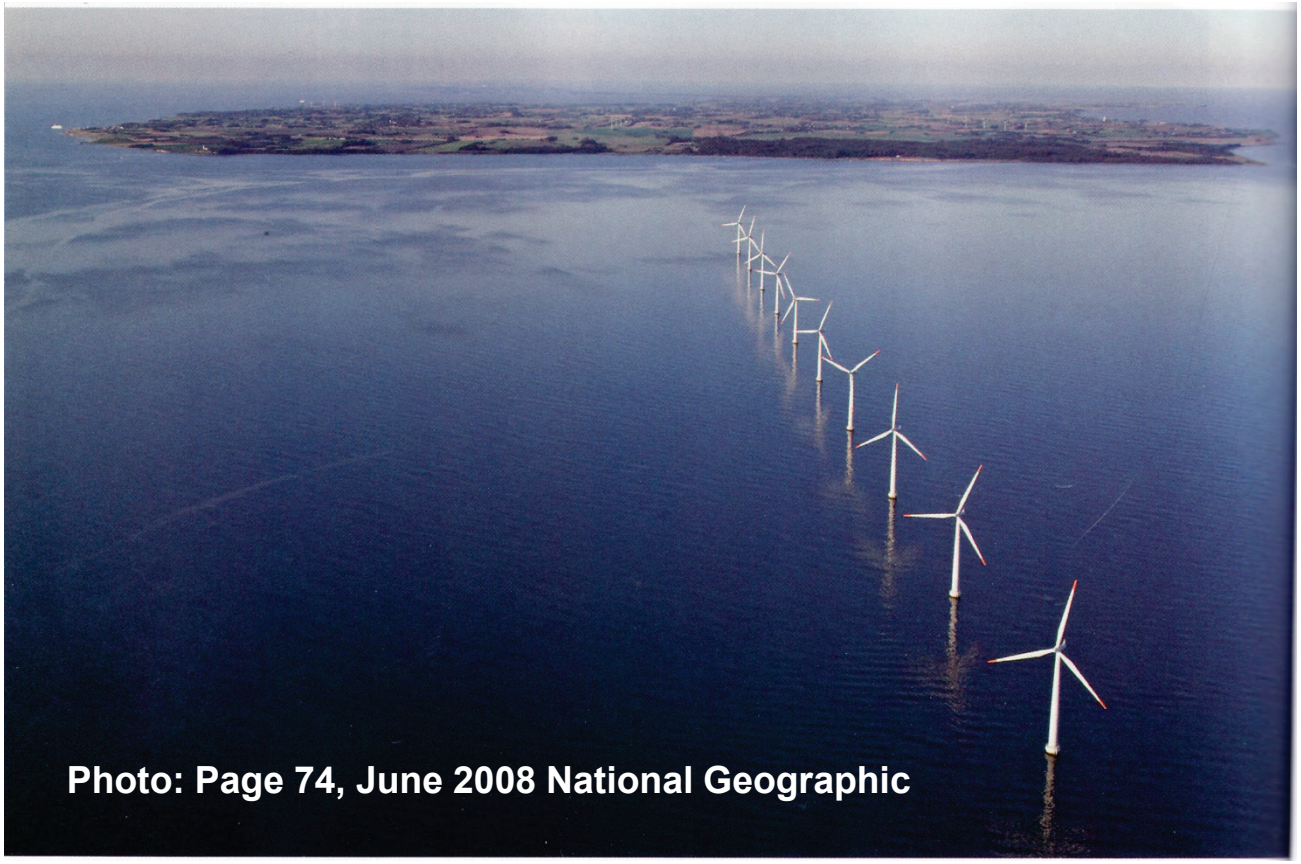
    June 29, 2003 - After a wind project was proposed several miles off the coast of Cape Cod, some environmentalists raised objections, as did U.S. Senator Ted Kennedy who owns a summer home in the area

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

Wind

Samsø, Denmark

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



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

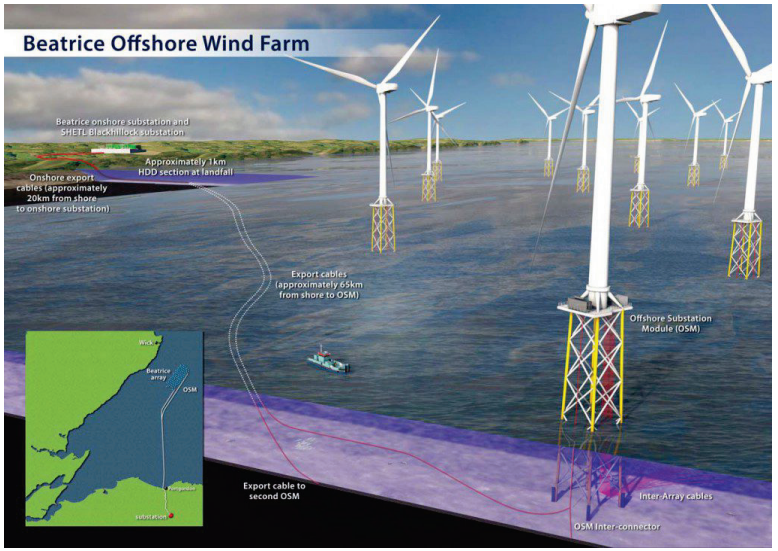
http://inapcache.boston.com/universal/site_graphics/blogs/bigpicture/earthday_04_23/e22_19972095.jpg

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

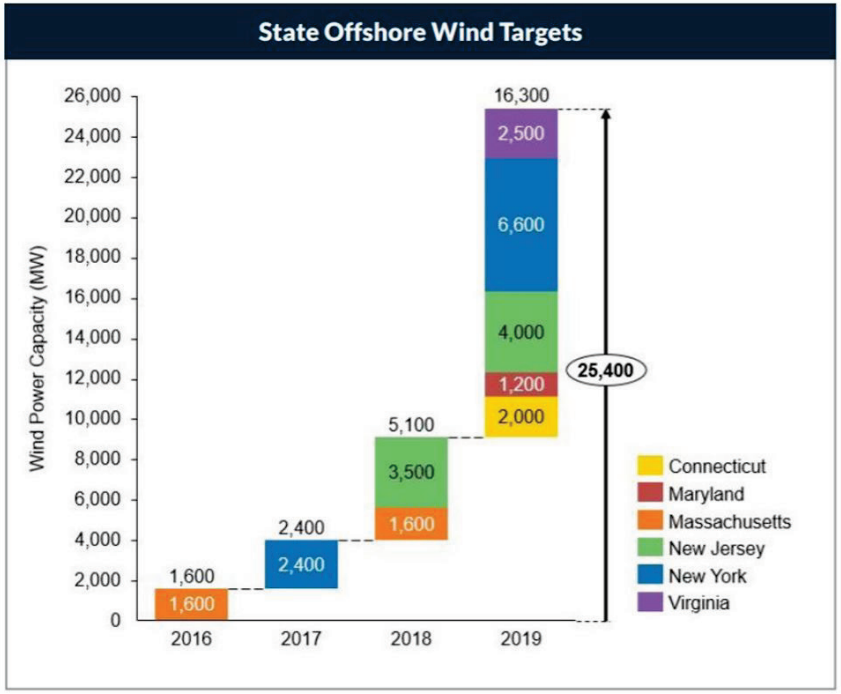
https://www.youtube.com/watch?v=1vy1ajBe8mY

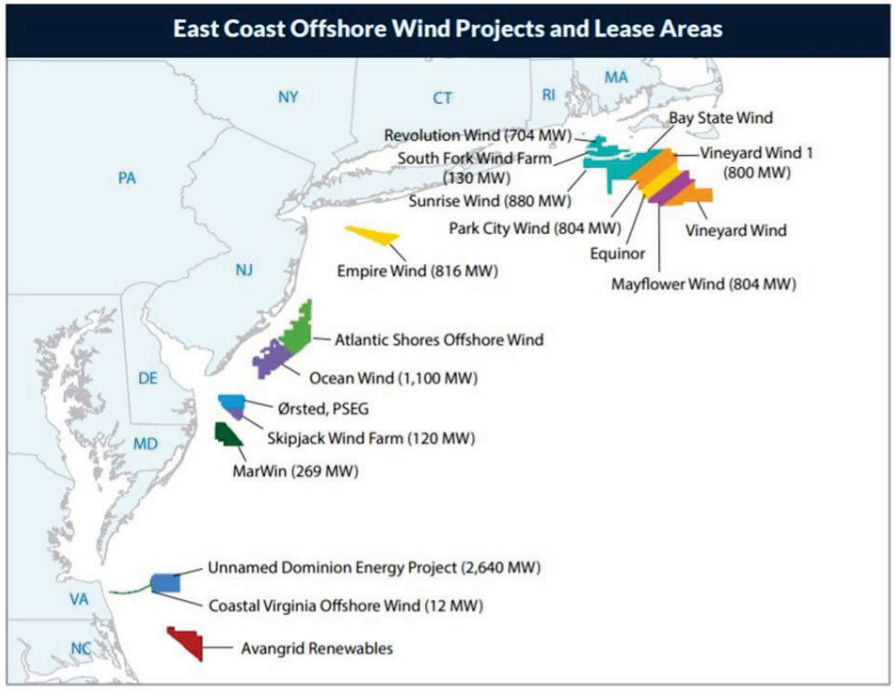
Offshore Wind, U.S.

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

Geothermal

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

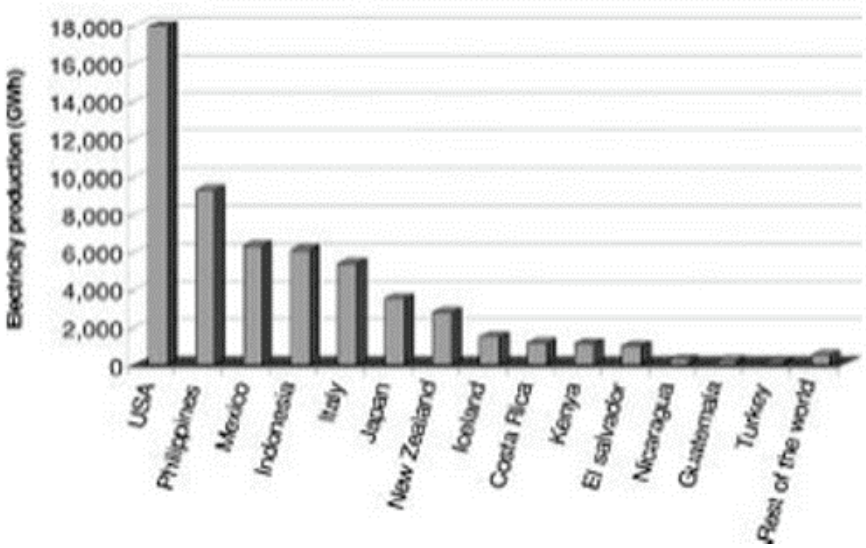


Figure 8.5 Geothermal electricity production, 2005. (Source: Bertani, R. [103].)

- 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:

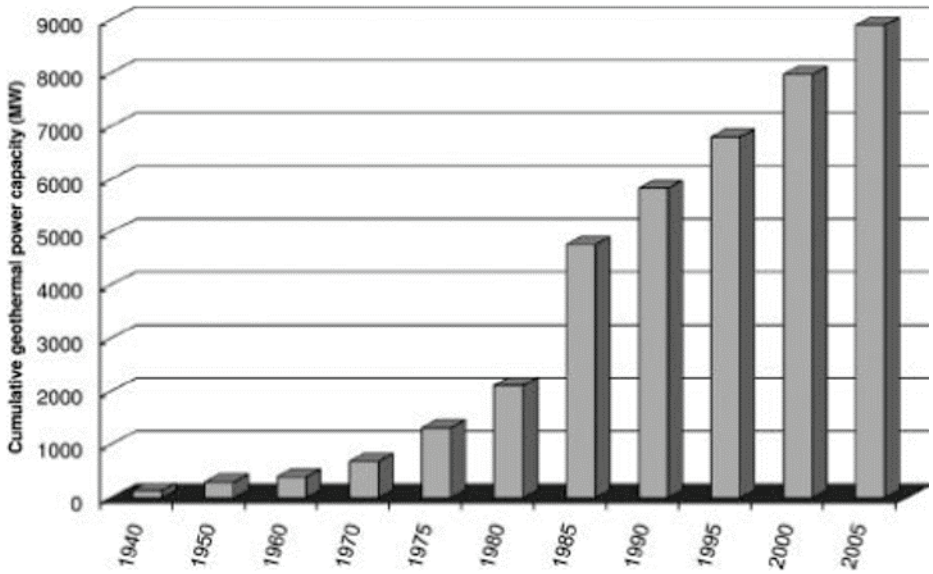


Figure 8.6 Worldwide development of geothermal electric power.

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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?

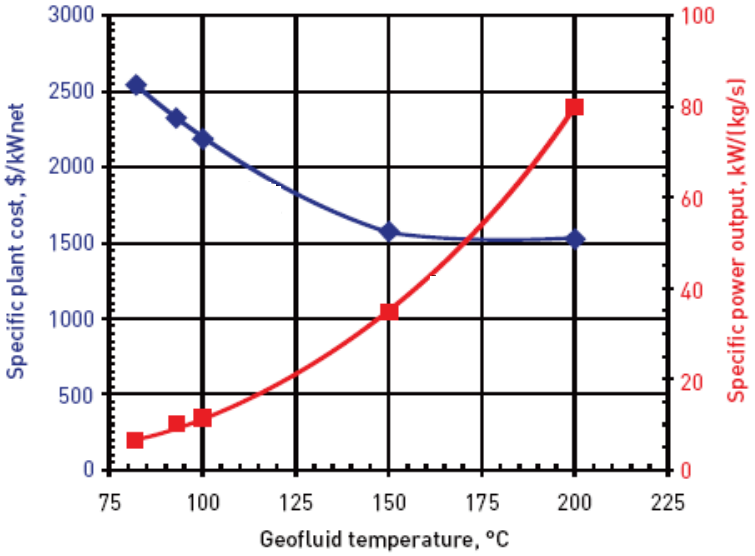
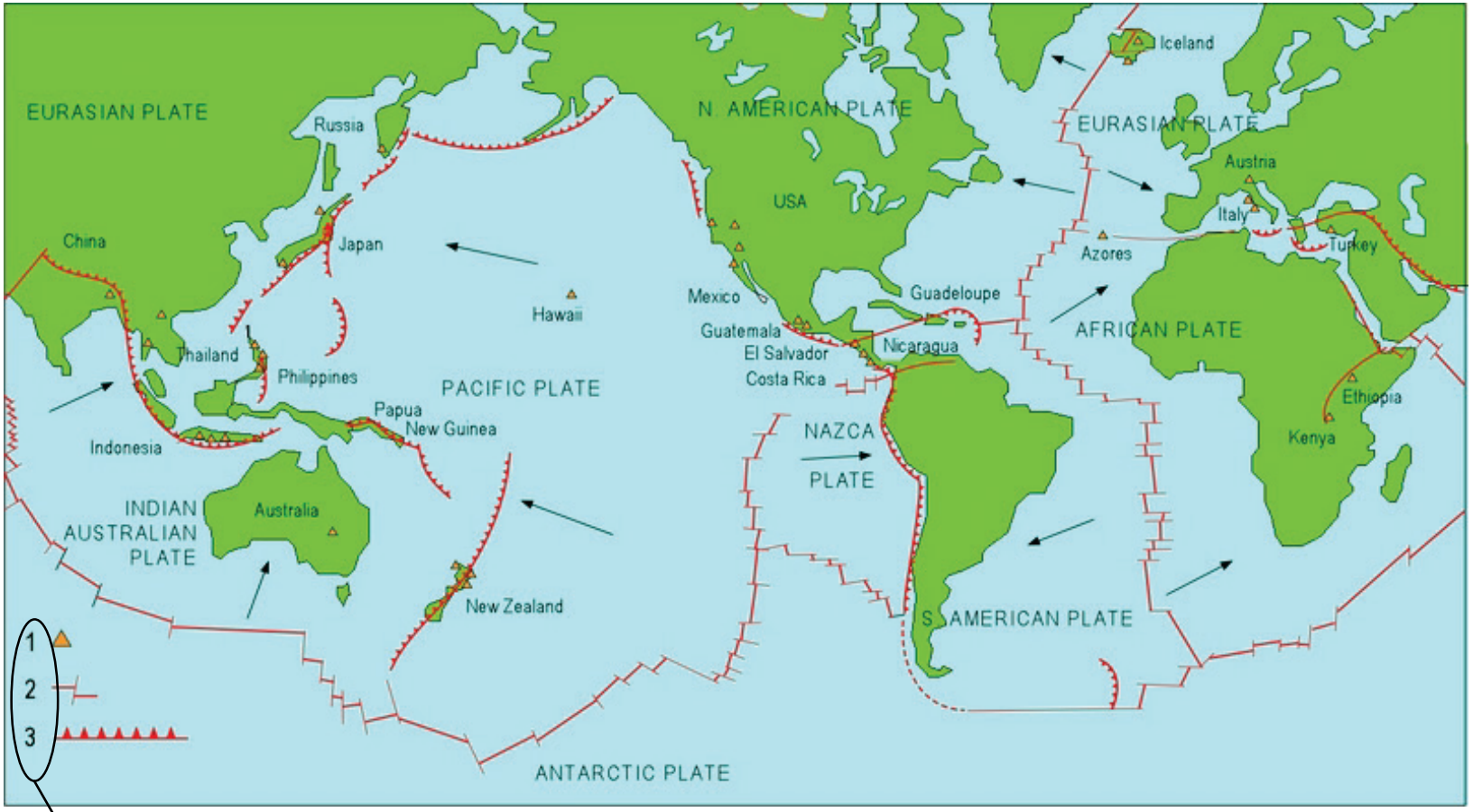


Figure 7.4 Cost and performance of 1 MW binary power plants as a function of geofluid temperature in degrees Celsius (°C).

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

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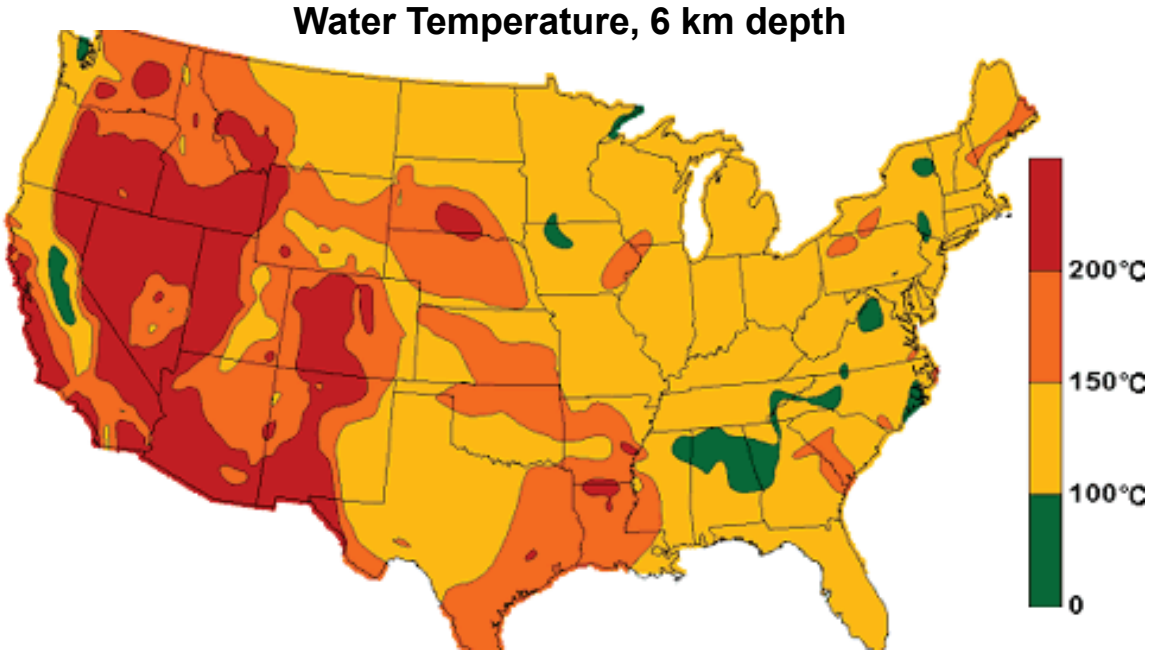
Map of U.S. Water Temperature



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.

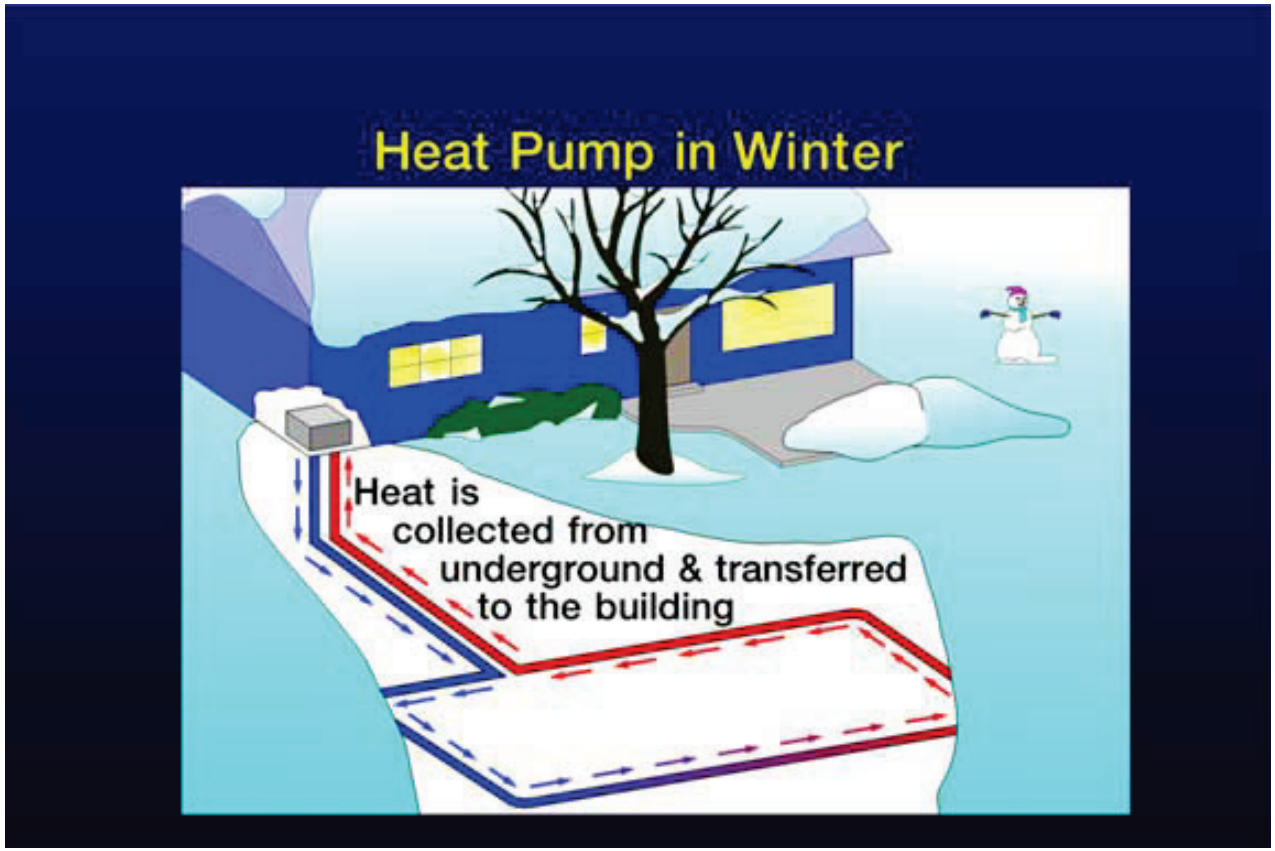
http://geothermal.marin.org/geopresentation/sld095.htm

Geothermal Heating

These pumps are used to pump the heated water to buildings in a district heating system, after it has passed through the heat exchanger.

http://geothermal.marin.org/geopresentation/sld093.htm

Low Earth Geothermal ***Heating***



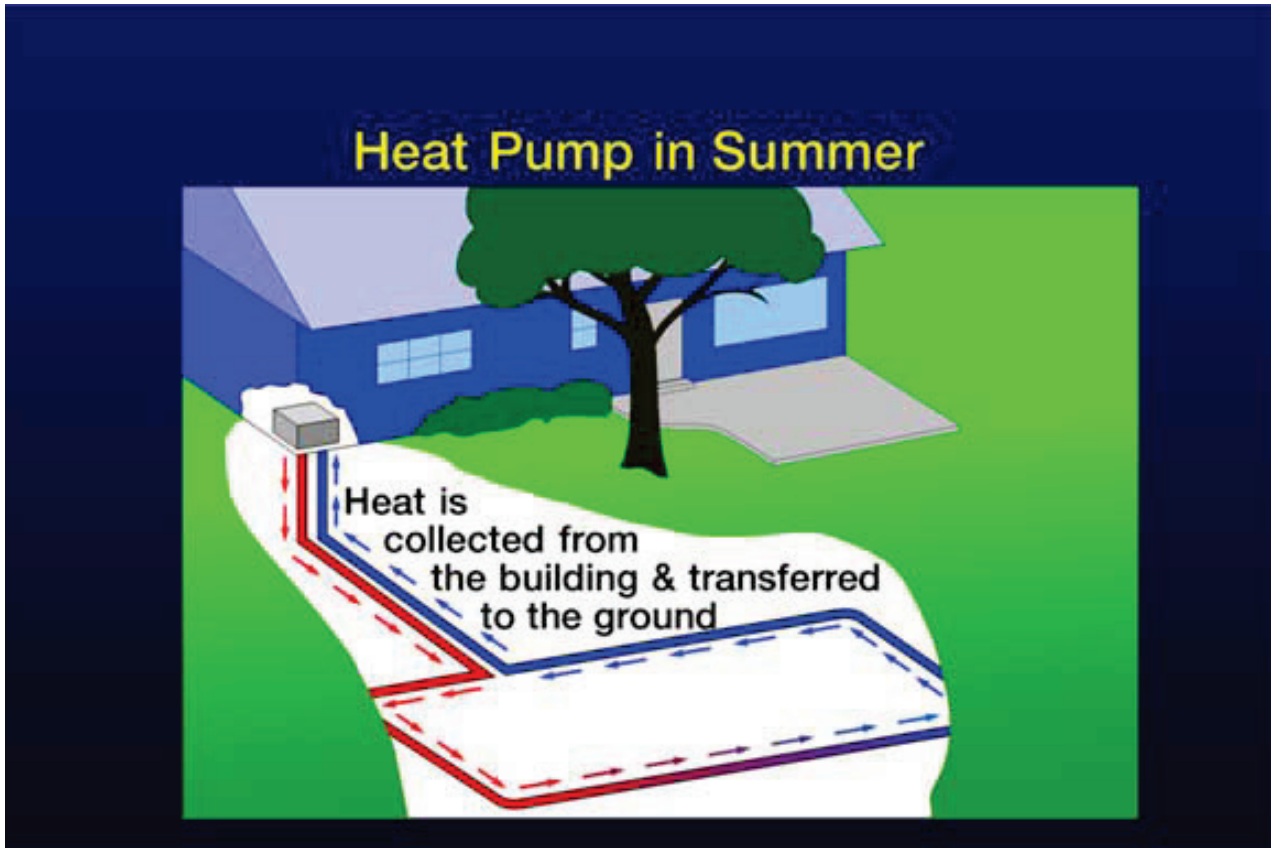
Winter: pump drives fluid to transfer energy from ground to building

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

Low Earth Geothermal ***Cooling***

How would this be done ?

Low Earth Geothermal ***Cooling***



Summer: pump reverses direction, drives fluid to transfer energy from building to ground

http://geothermal.marin.org/geopresentation/sld103.htm

Geothermal Heating/Cooling

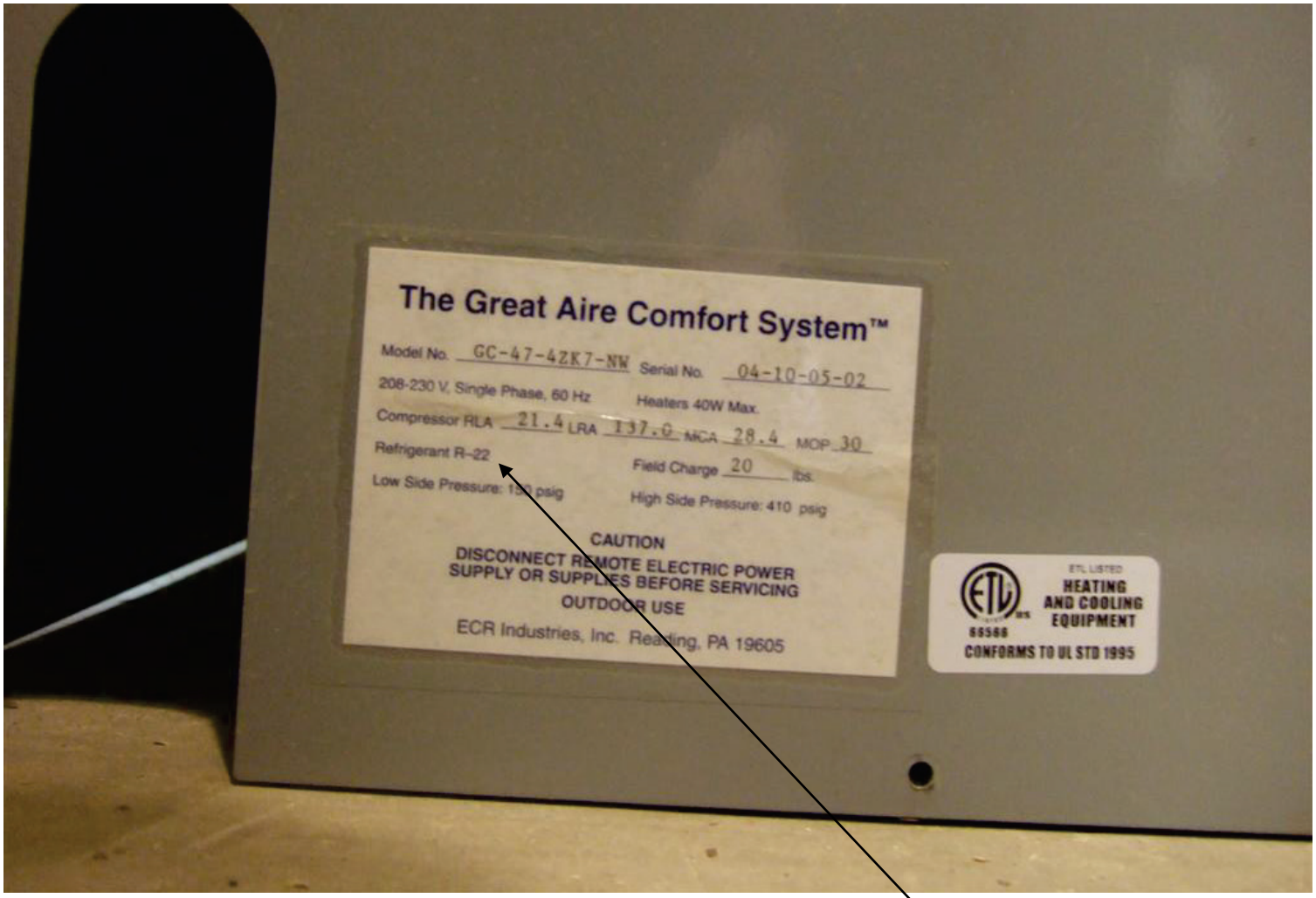
Geo-thermal heating/cooling at local church:

Paint Branch Unitarian / Universalist, Adelphi, Md

Geothermal Heating/Cooling

Geo-thermal heating/cooling at local church

Geothermal Heating/Cooling



R-22: HCFC-22 ($CHClF_2$)

Geothermal Heating/Cooling

Geo-thermal heating/cooling at local church:

Structure heated and cooled by geothermal

6 units, installed 2005 at cost of _____ ?

Geothermal Heating/Cooling

Geo-thermal heating/cooling at local church:

Structure heated and cooled by geothermal

6 units, installed 2005 at cost of $200,000 !