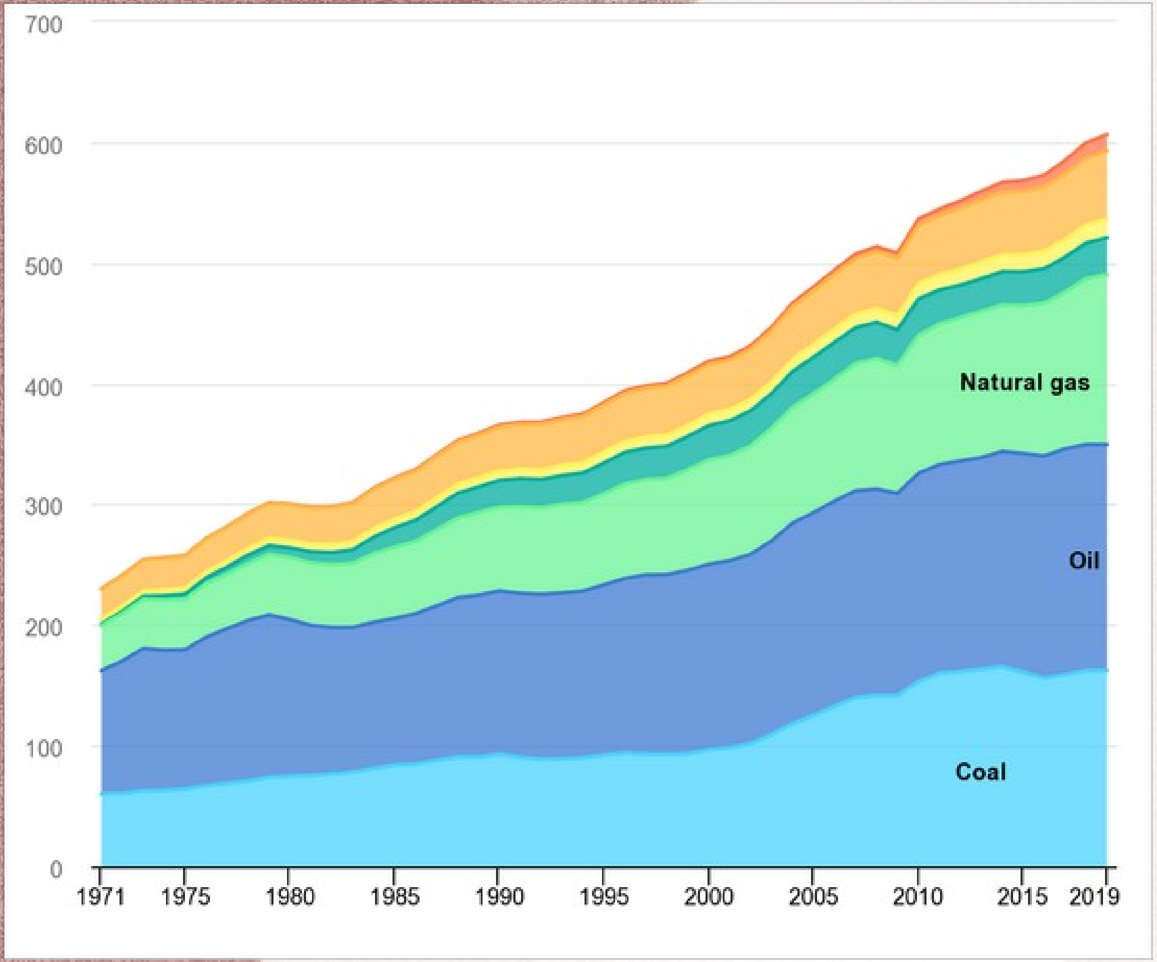
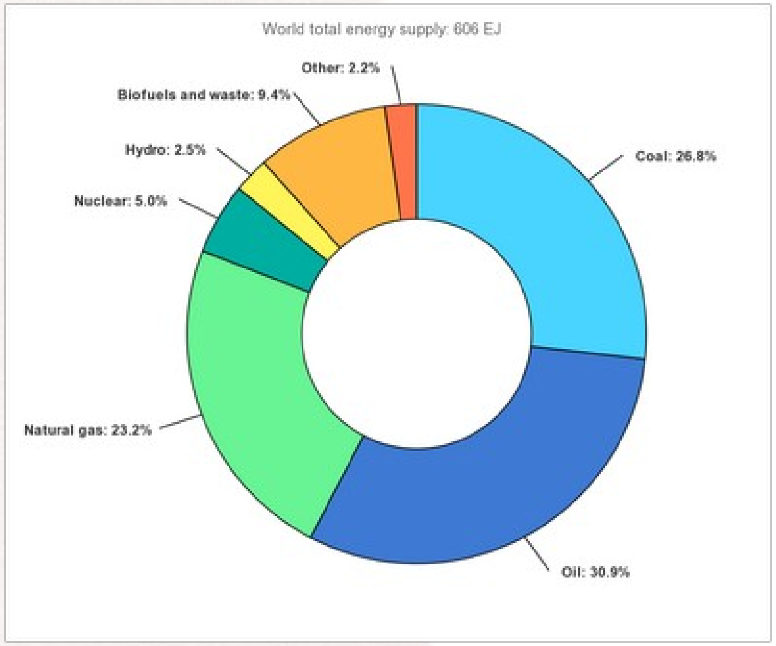
Sustainability in Civil Engineering

V. Energy

Where does commercial energy come from?



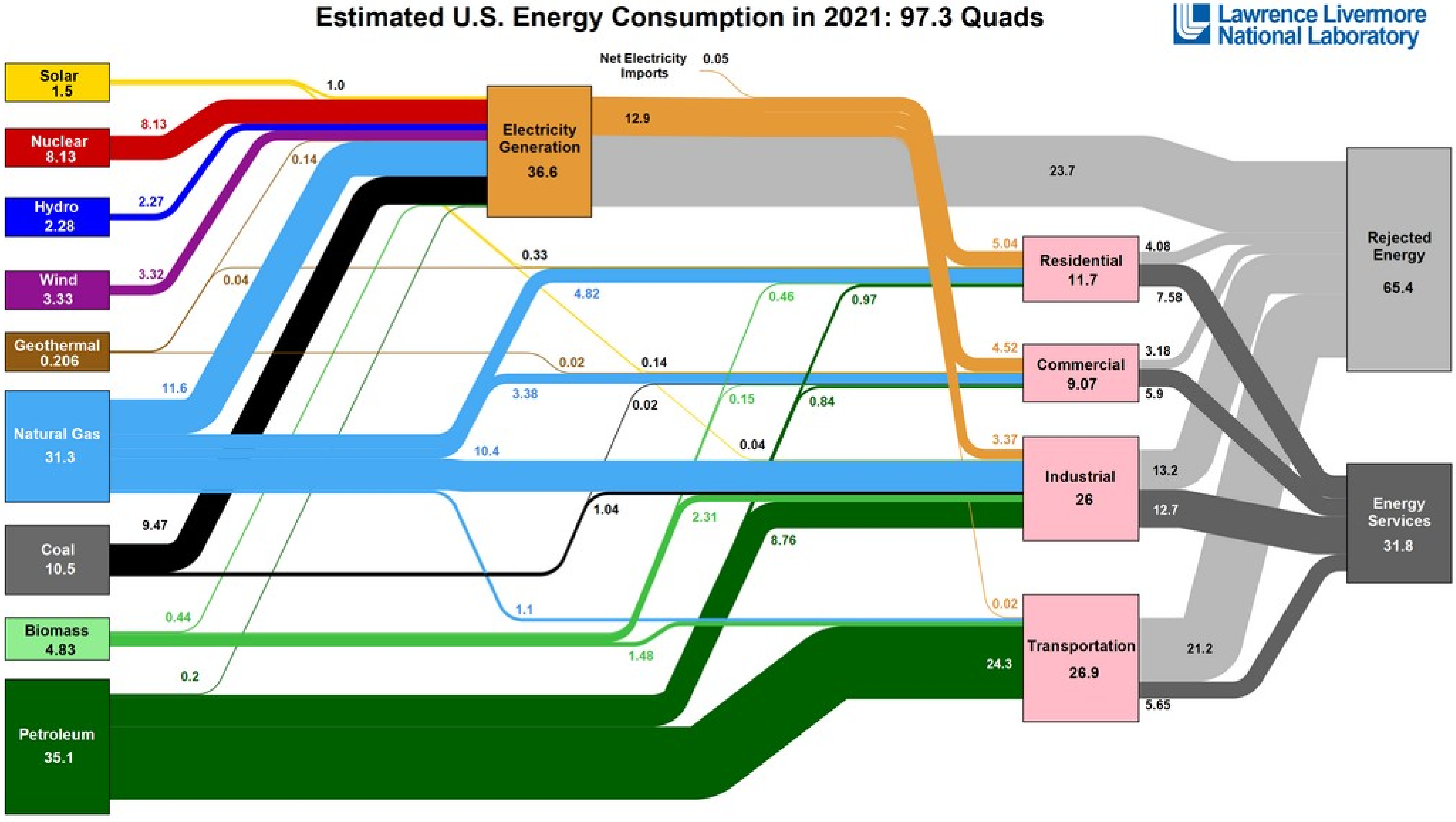


mostly, fossil fuels

IEA Key World Energy Statistics
units: EJ (per year)

Conversion efficiency, primary energy to electricity (via heat engine): 30-60%

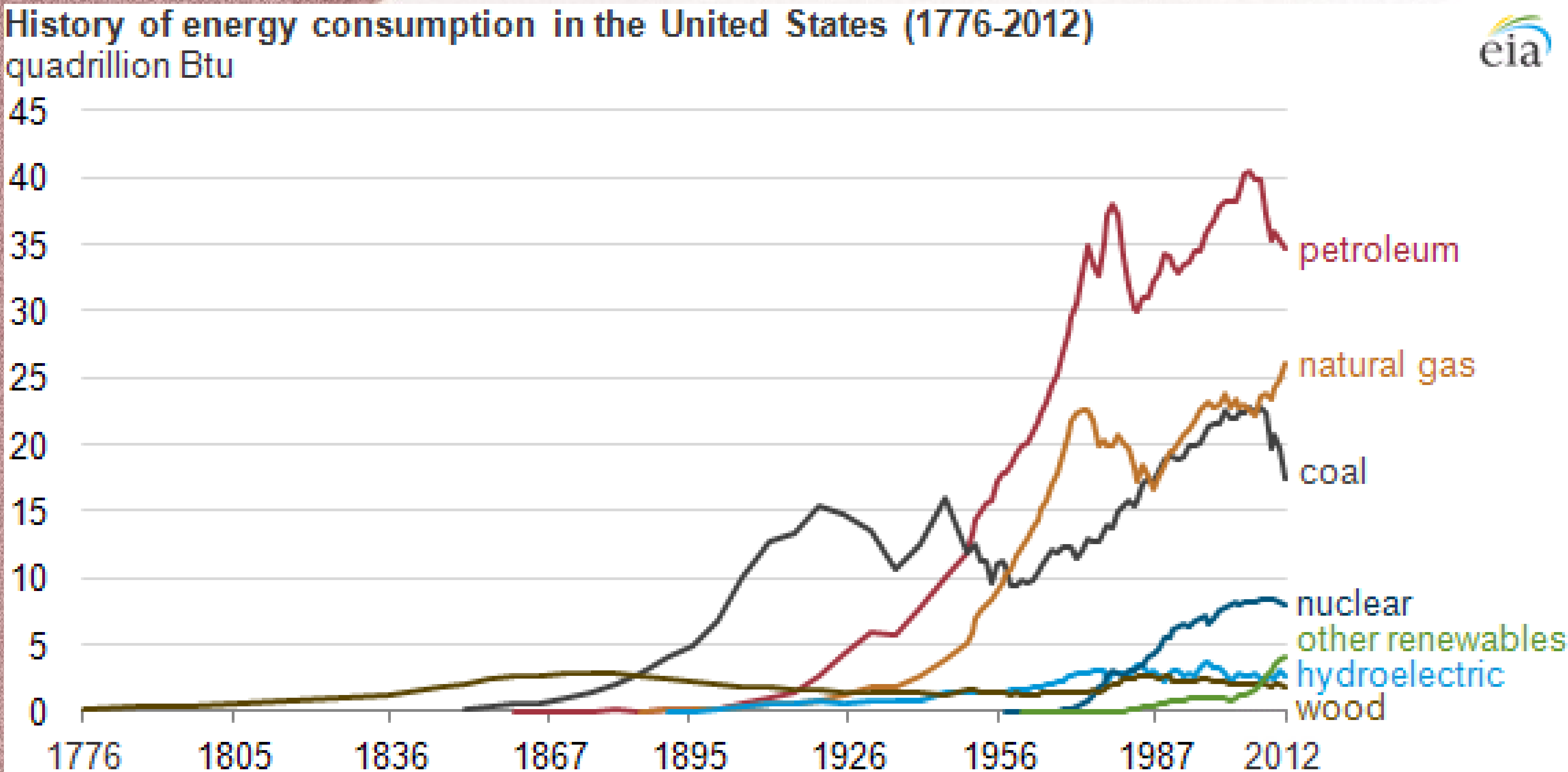
Fuel to end use



Source: LLNL March, 2022. Data is based on DOE/EIA MER (2021). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 21% for the transportation sector and 49% for the industrial sector, which was updated in 2017 to reflect DOE's analysis of manufacturing. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

Why are particular fuels associated with particular end uses?

Changes in fuel mix

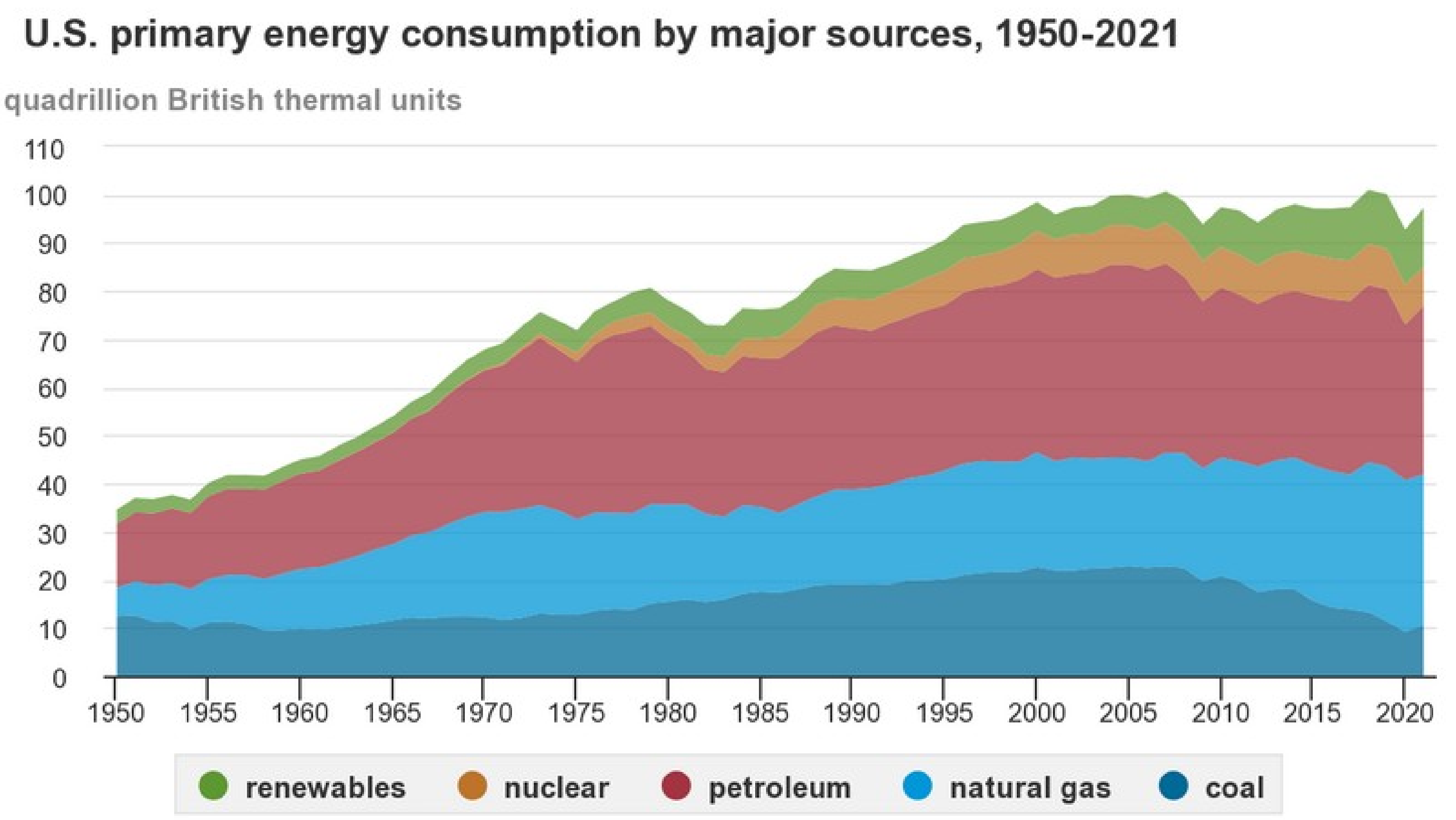


What caused these changes in US energy consumption and sources?

How long has it taken new energy sources to catch on?

Solar/wind have increased rapidly recently (but are still small)

Changes in fuel mix



Data source: U.S. Energy Information Administration, *Monthly Energy Review*, Table 1.3, April 2022, preliminary data for 2021
Note: Petroleum is petroleum products excluding biofuels, which are included in renewables.

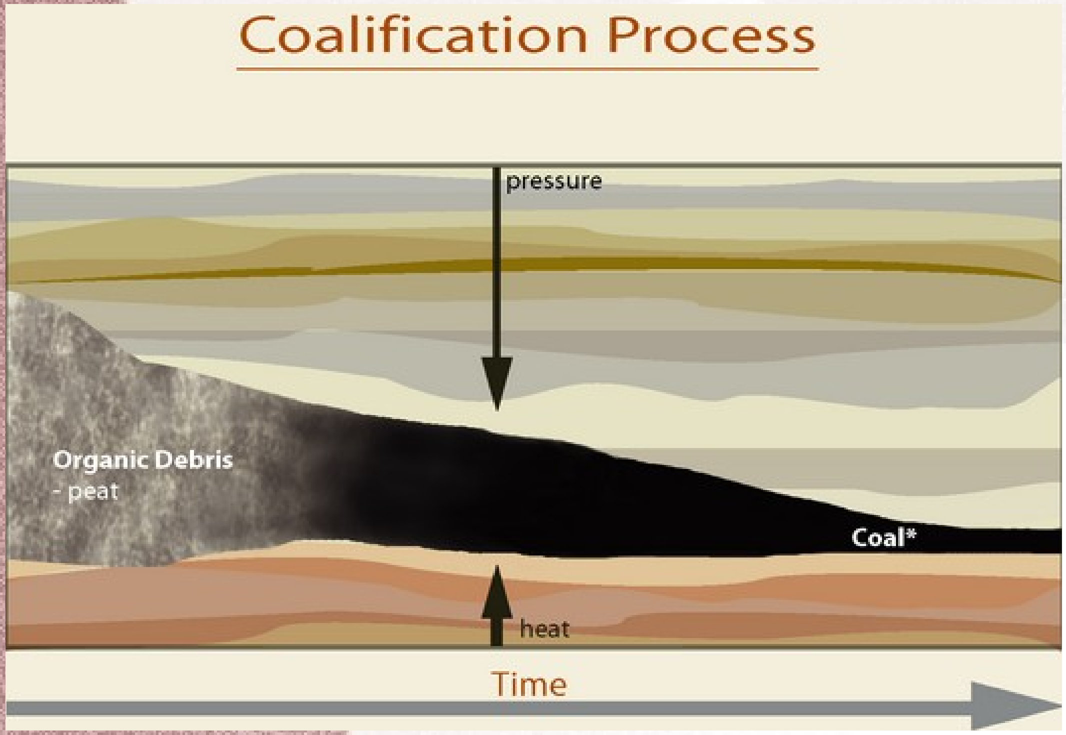
What caused these changes in US energy consumption and sources?

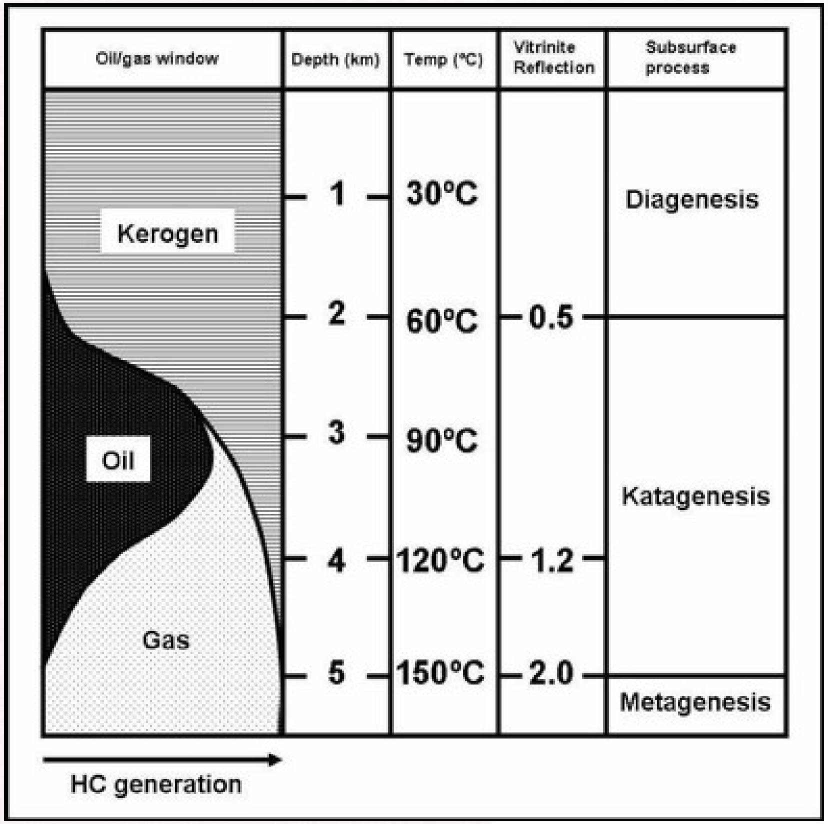
Energy sustainability challenges

- Fossil fuel energy is not sustainable
  - Pollution, esp. global warming (timescale for transition: ASAP)
  - Exhaustion of resources (timescale: decades)
  - Geopolitics/security (ASAP)
- Renewable solar energy is abundant, but faces technical and political obstacles
- Even leaving the fuel source aside, USA investment in energy infrastructure is too small and misdirected (ASCE C- grade [2021], hurricanes, ice)

Specific energy sources

Where do fossil fuels come from?





Fossil sunlight – dehydrated, partly pyrolyzed dead plants (or algae)

Oil and gas rise, so need *reservoir* and *cap* formations as well as a *source* formation

Coal burning

- Used as fuel in prehistoric time; "the Romans were exploiting coals in all the major coalfields in England and Wales by the end of the second century AD"
- Widely replaced wood for heating and ironworking in China (11th Cent.) and Britain (16th Cent.)
- Starting with coal-powered steam engine to help with coal mining, burning has increased 100x since 1840, 10x since 1890, 2x since 1980

Coal today

- Mostly used for large-scale electricity generation (1.2 TW electricity), secondarily for ironworking
- Burning: China (54%, of which 10% is imported from Indonesia, Russia), India (12%), USA (7%)
- 44% of fossil fuel burning CO_2 emissions (oil: 33%, gas: 23%)
- Largest reserves: USA (23%), Russia (15%), Australia (14%), China (13%), India (10%)
- Proved reserves supposedly 130 y current mining. Price ~doubled since 2003, and fluctuates

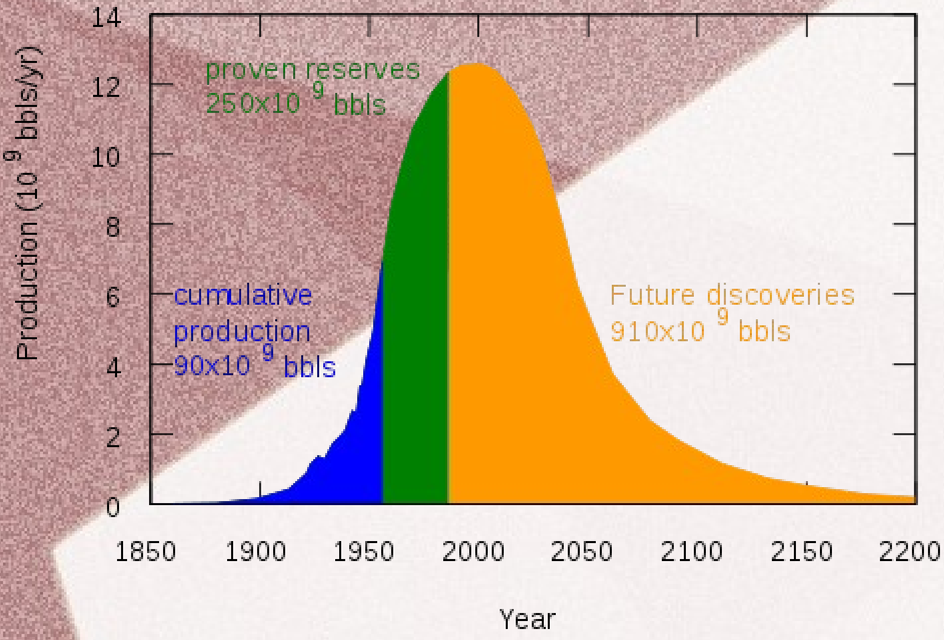
Oil and gas history

- Oil from seeps long used (e. g. in Babylon); first wells for oil and gas drilled in China by 400, partly associated with the inland search for salt
- Drilling intensifies in 1850s (Galicia, Baku, Romania) for kerosene lamps
- Mining rate increased 100x since 1910, 10x since 1945, 2x since 1970
- Natural gas used for streetlights in 19th cent., more widely for heating and electricity since WWII
- Mining rate increased 100x since 1920, 10x since 1955, 2x since 1990

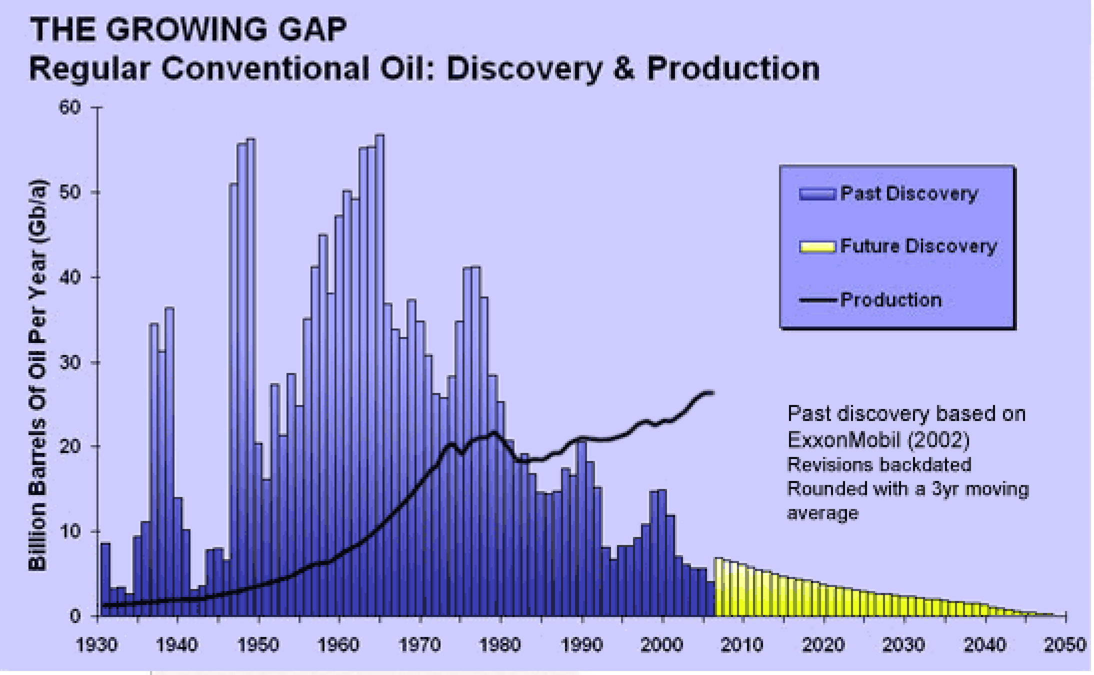
Oil today

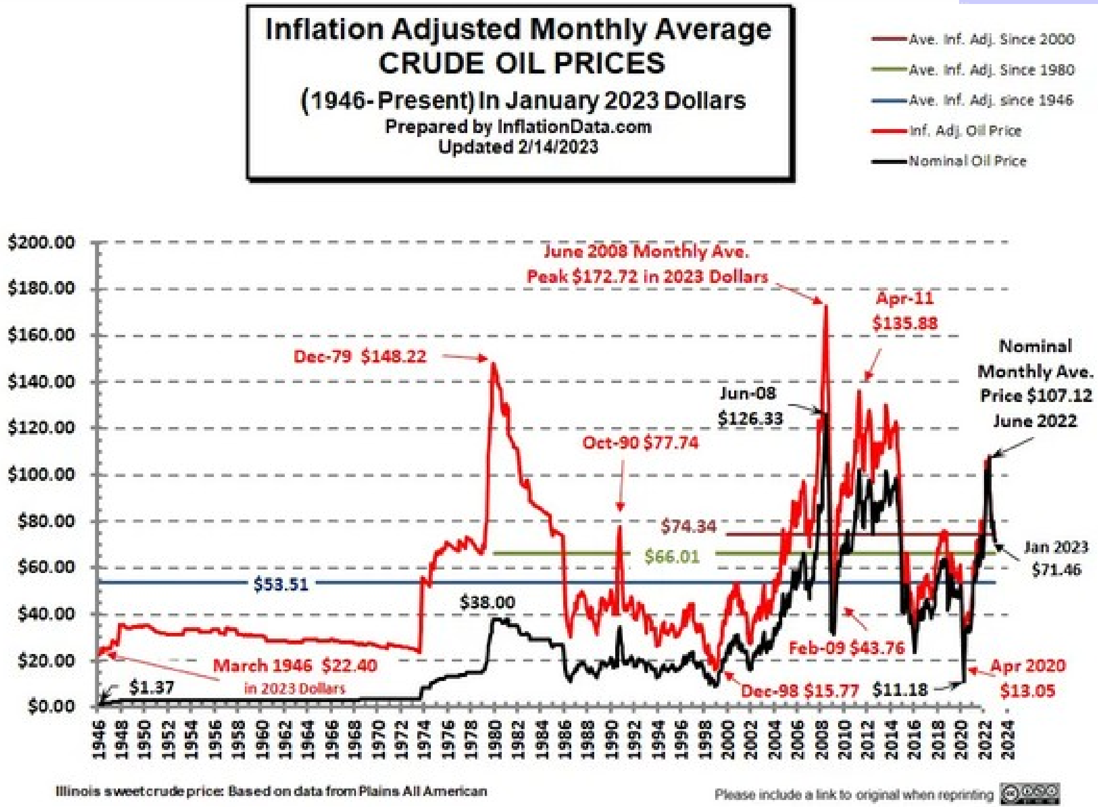
- Mostly used for transport (runs almost all cars, trucks, planes, ships), secondarily chemicals (locally used for heating)
- Burning: USA (19%), China (17%), India (5%), Japan (4%)
- Mining: USA (19%), Russia, Saudi Arabia (12% each), Canada (6%), Iraq (5%), Iran, China, UAE (4% each)
- 48% reserves in Mideast, 18% in Venezuela, 10% in Canada (tar sands), 6% in Russia, 4% in USA
- Reserves supposed 50 y production; production rate increasing 1%/year
- Low prices since 1880s, \$20-\$30/bbl post-WWII; price shocks 1973-85 and 2007-2014

Peak oil?



Hubbert (1956)





Gas today

- Mostly used for electricity generation (700 GW) and heating
- Burning: USA (21%), Mideast (14%), Russia (12%), EU (12%), China (9%)
- Mining: USA (23%), Mideast (18%), Russia (17%), EU (5%), China (5%)
- 40% of reserves in Mideast (Iran, Qatar), 20% in Russia, 7% in USA, 5% in China, <2% in EU
- Reserves supposed 50 y production
- Price ~doubled since 1998 for Eurasia (though stable/declining in USA and Canada)

Nuclear energy

- 300 GW electricity from ^{235}U fission (25% of coal contribution, 65% of hydroelectric)
- Concentrated in USA (29%), China (15%), France (14%), Japan (10% pre-quake), Russia (8%)
- Most plants built in 1980s, output flat since 2000; some construction in China
- Future increases possibly limited by high-grade U ore supply, as well as by cost and public opinion
- Also a fossil fuel, in that geological processes that concentrated U ore happened slowly

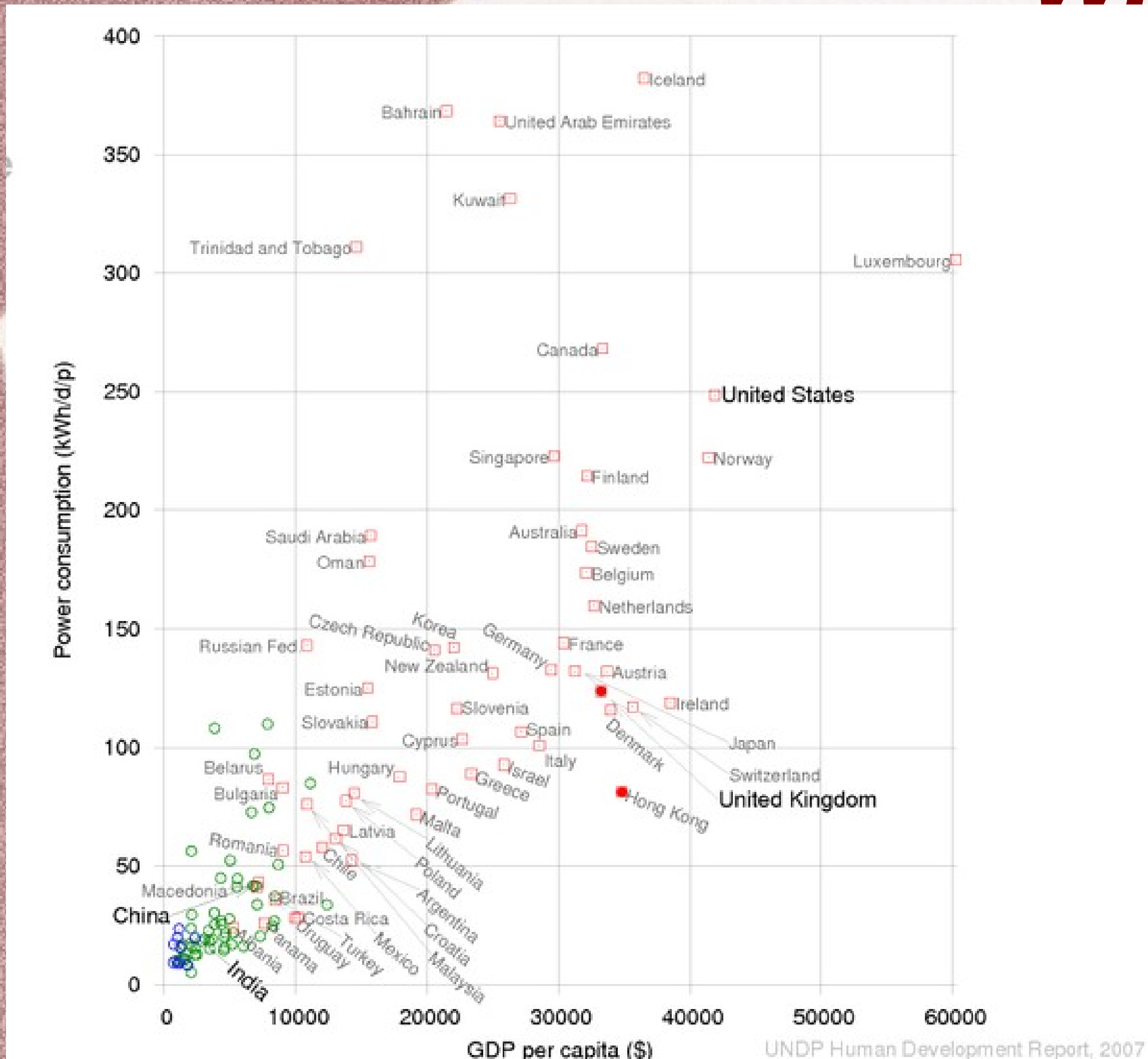
Environmental impacts of fossil-fuel use

- Mining and processing: oil spills, mountaintop removal, harm to miners...
- Burning: primary GHG contributor, particulates, smog, acid rain, Hg, radioactivity...
- All consequences are accepted because it’s hard to imagine life without fossil-fuel energy. Can we?
- Each year, we burn about a million years’ accumulation of fossil fuel deposits

Fluxes of renewable exergy

- W / m^2:
  - Sunlight: 200
  - Solar electricity: 30
  - Tides (good sites): 5
  - Wind (good sites): 3
  - Biofuels: 0.4 (temperate) to 1.2 (tropics)
  - Hydroelectric: 0.25 (per unit catchment area)
  - Geothermal flux: 0.1
- Primary energy use (mostly fossil) per unit land area:
  - World: 0.1
  - USA: 0.3
  - UK: 1.1
- Conclusion: a renewable-based energy system
  - requires lots of land
  - should be based directly on sunlight
  - would benefit from energy conservation

In fact, we could certainly manage with less energy



USA primary energy consumption was lower in 2019 than in 2000, despite 17% more people and lots more gadgets, yet still is high compared to other wealthy countries

In subsequent classes, we will consider in more detail sustainable options that reduce requirements drastically

What characteristics would we like from our energy supply?

- Electricity
  - Constantly available, at least for essential uses; some uses can be postponed minutes, hours, or days
- Transport
  - Portable (light, compact), or follow the vehicle (e.g. electrified rails)
  - Also needs portable construction, maintenance machines
- Chemical
  - Primarily organic materials (food, wood, textiles, pharmaceuticals, plastics, carbon fiber, coke, perhaps fuel...)

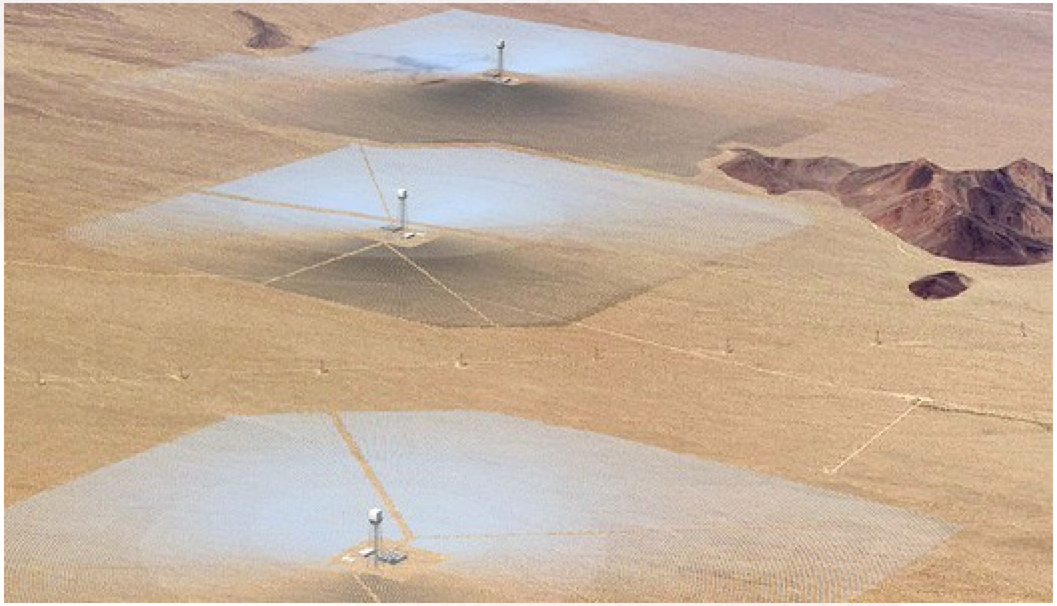
Technical issues with renewable energy (Post-Carbon Institute)

- 1. Scalability and Timing
- 2. Commercialization
- 3. Substitutability
- 4. Material Input Requirements
- 5. Intermittency
- 6. Energy Density
- 7. Water
- 8. The Law of Receding Horizons
- 9. Energy Return on Investment

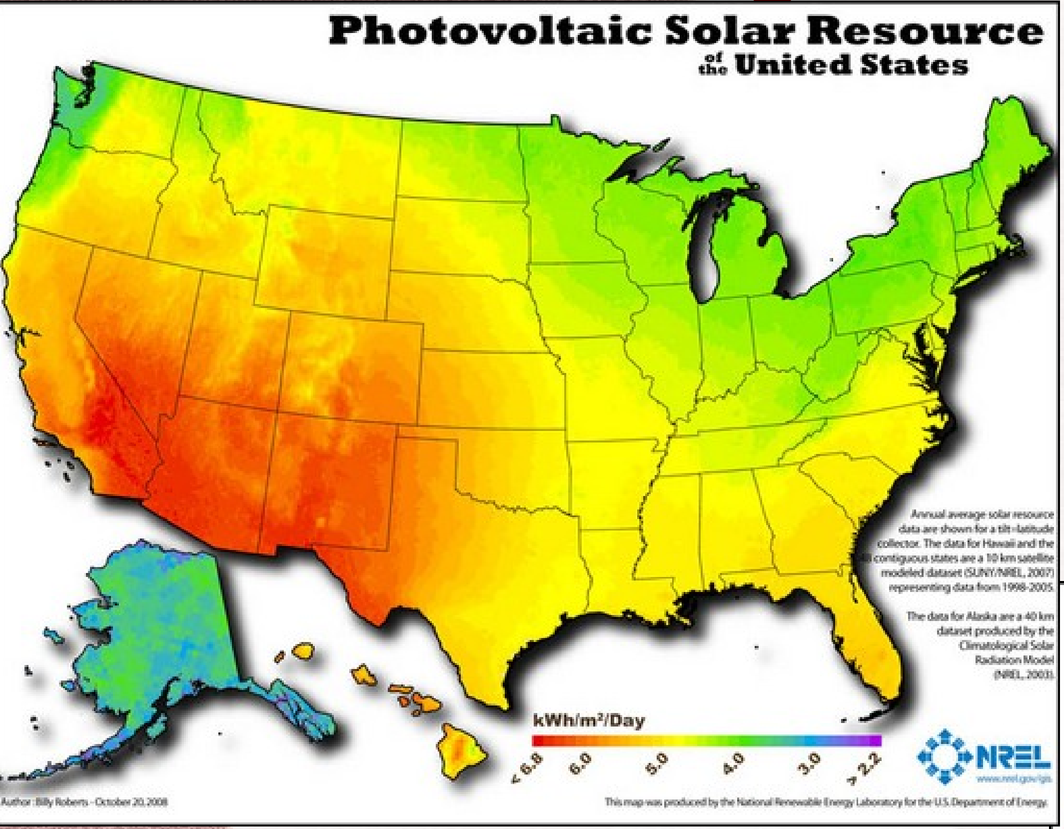
Electricity from sunlight

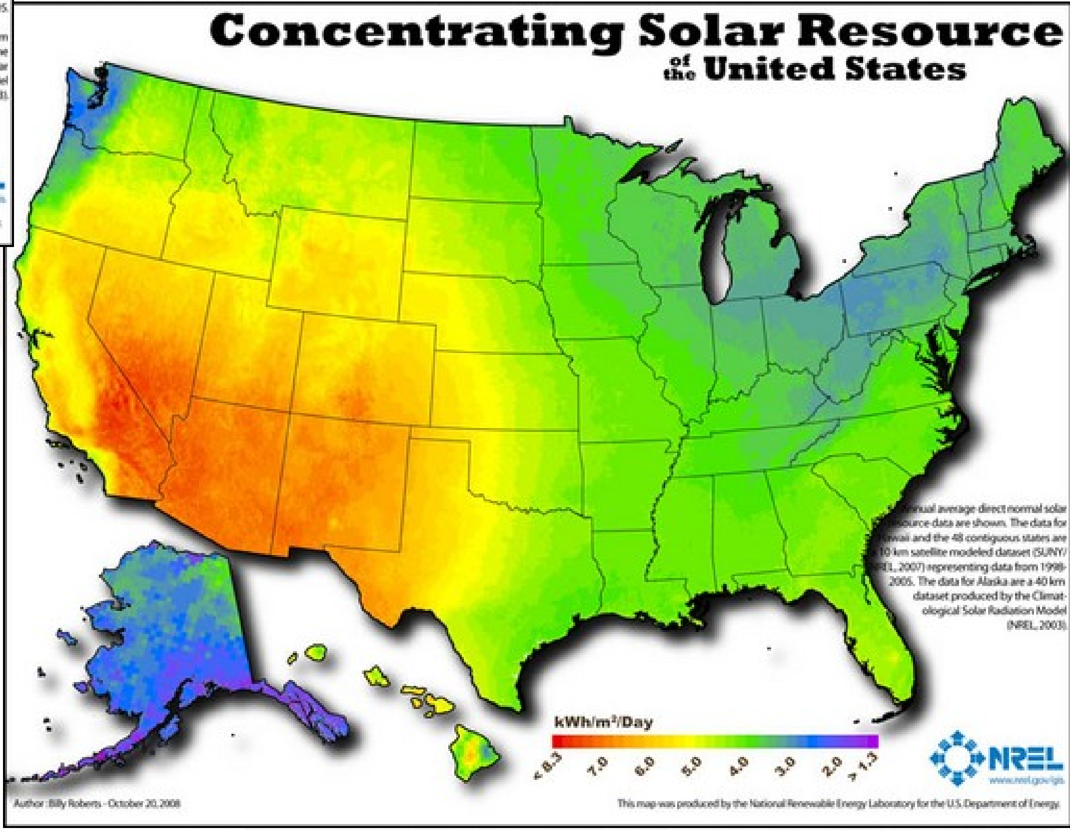
- Photovoltaic: light striking a semiconductor generates an electric current

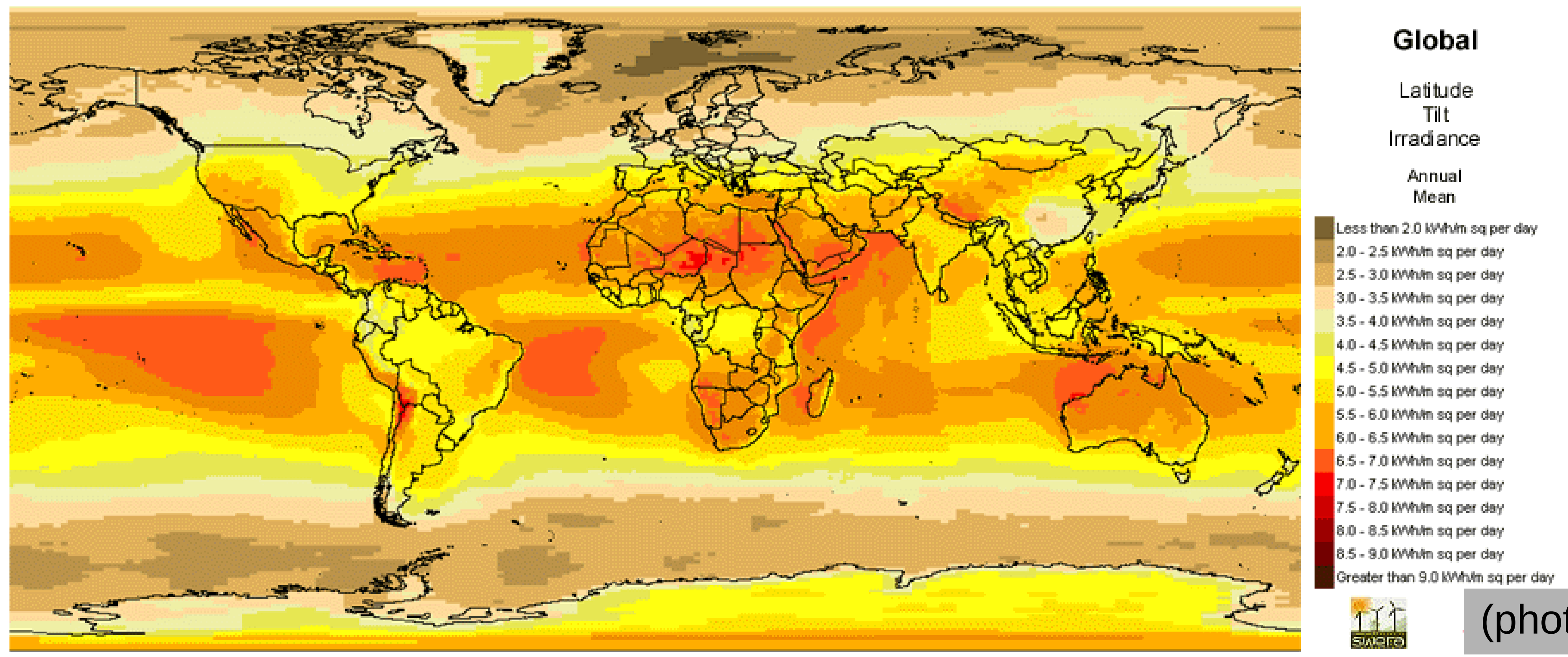
- Thermal: concentrated sunlight boils water, running a heat engine



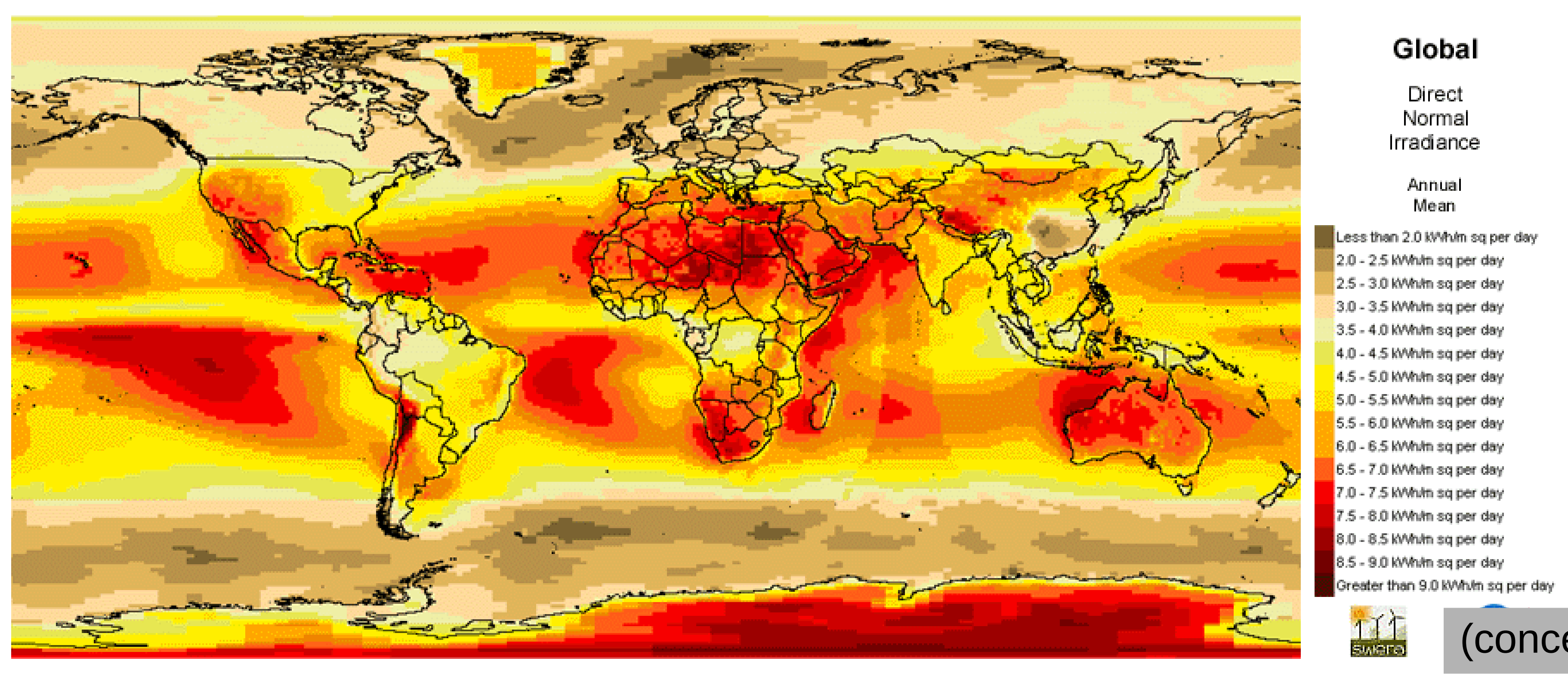
Sunlight is widely distributed







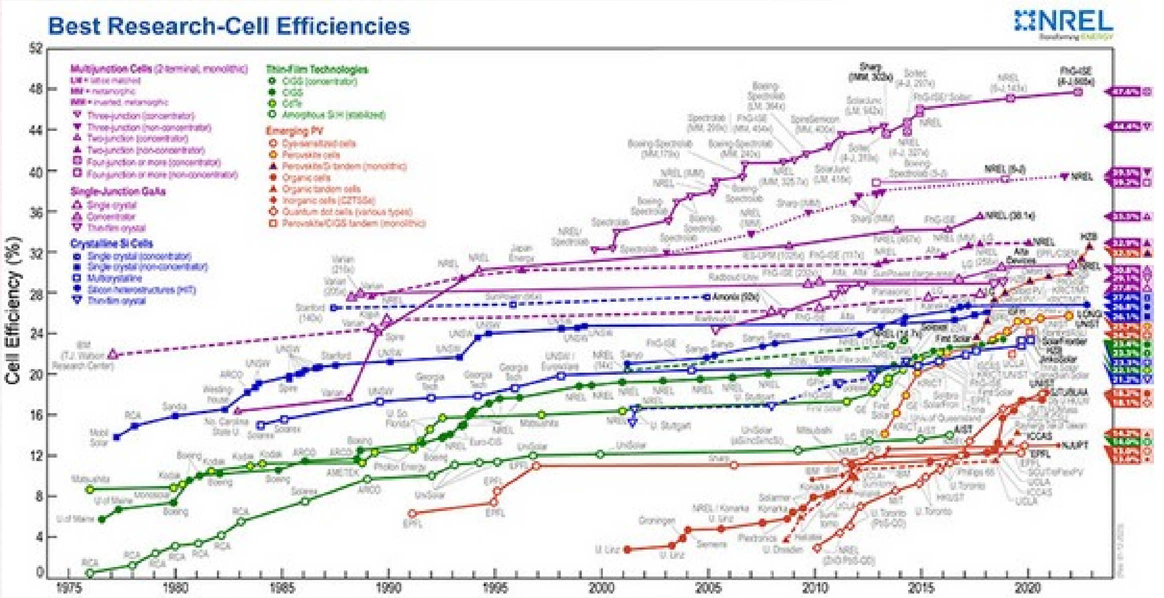
(photovoltaic)



(concentrating)

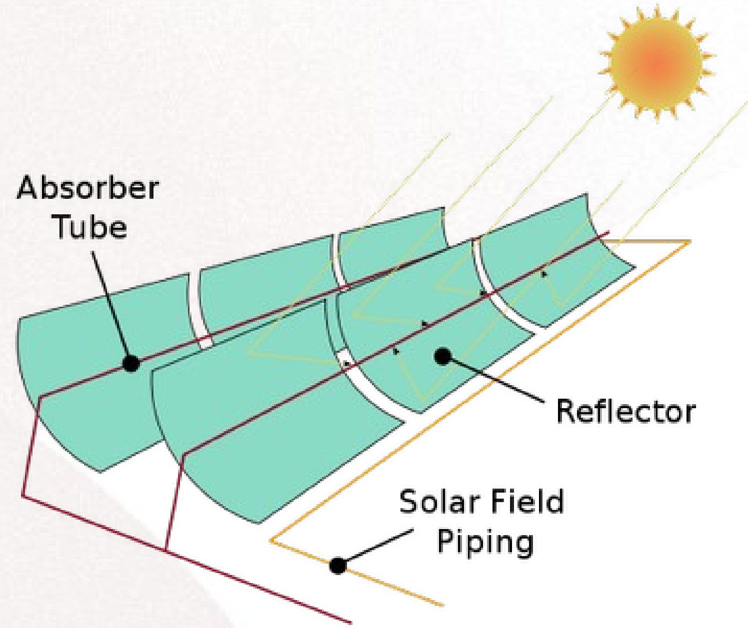
Photovoltaic cells

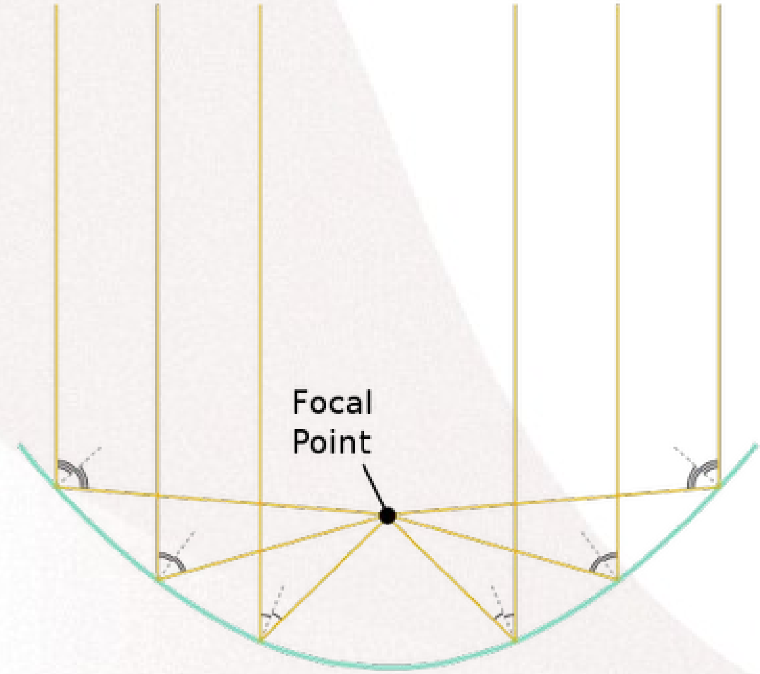
- Developed for spacecraft; market helped by incentives
- 900 GWp as of 2021 (2% global electricity), increasing >30%/year: China (32%), USA (16%), Japan (8%), Germany (5%)
- Typical cost: ~$1/Wp (large-scale), $3 (residential)
- Usable in all climates; roof of house could provide domestic electricity needs (but intermittent)



Solar thermal

- Developed starting in late 1800s; various designs for focusing and heat engine
- 7 GWp. Built in Cali. in 1980s; resurgent interest since 2005 (Spain); since 2012 getting undercut by PV
- Concentrating PV / combined heat and power possible

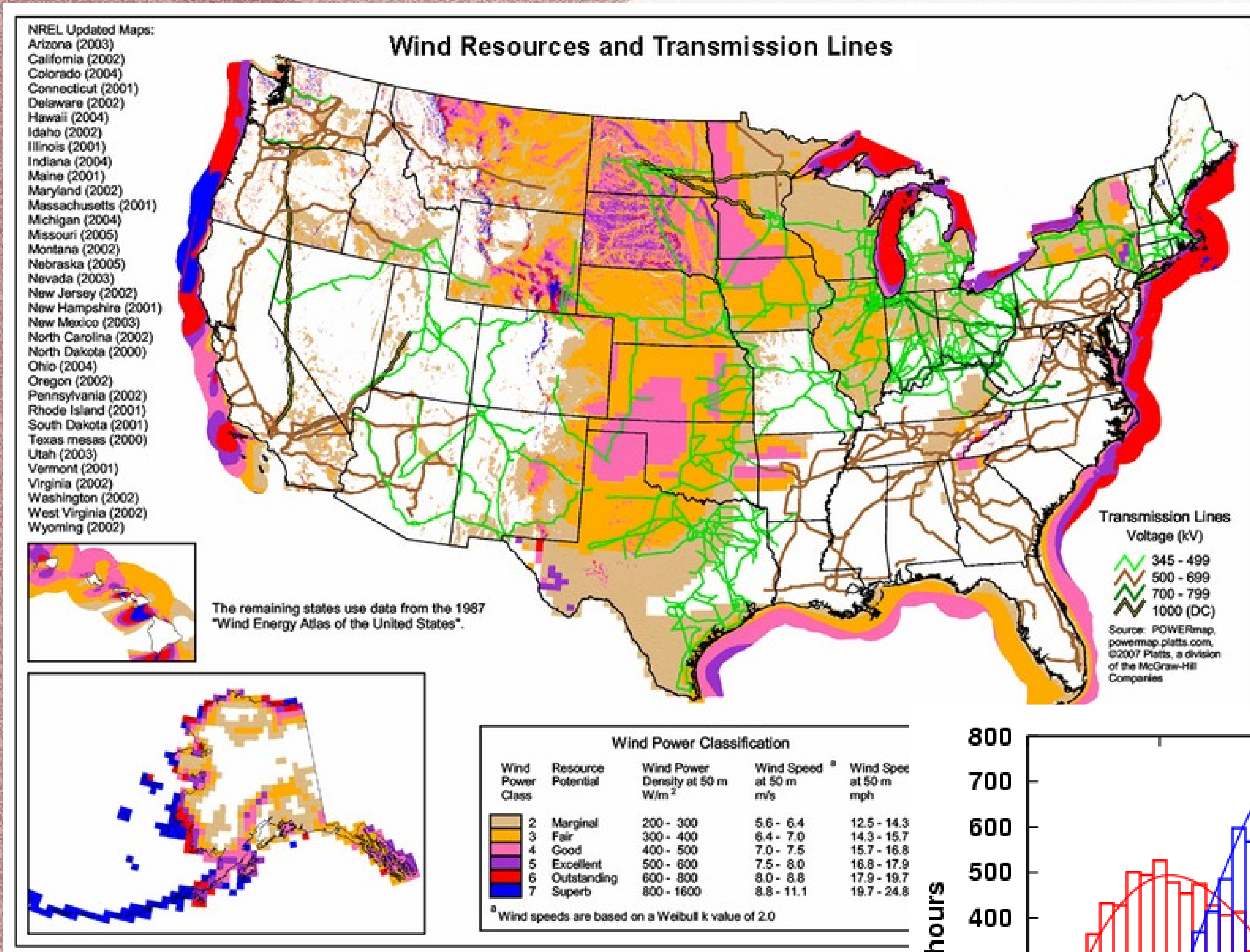




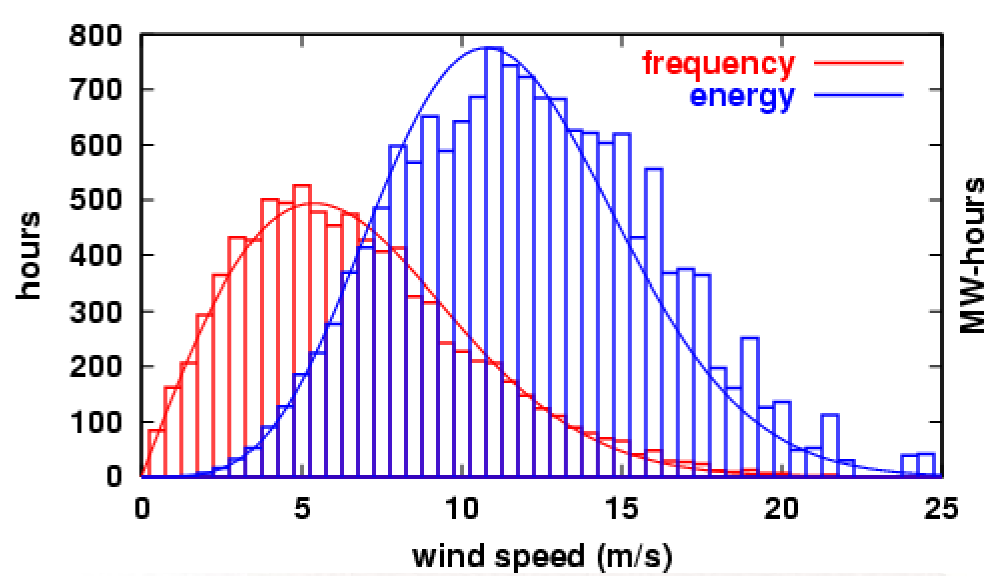
Solar thermal with storage

- Can store heat for generating electricity on demand at night – need large amount of storage material (salt or sand)
- Archimede plant (Sicily, 5 MW), completed 2010 at $16/Wp; several 100-MW scale in Spain, SW USA
- DESERTEC initiative: generate power in Sahara and transmit some to Europe (can use the heat for water desalination)

Windiness



Wind Resources and Transmission Lines
NREL Updated Maps:
Arizona (2003)
California (2002)
Colorado (2004)
Connecticut (2001)
Delaware (2002)
Hawaii (2004)
Idaho (2002)
Illinois (2001)
Indiana (2004)
Maine (2001)
Maryland (2002)
Massachusetts (2001)
Michigan (2004)
Missouri (2005)
Montana (2002)
Nebraska (2005)
Nevada (2003)
New Jersey (2002)
New Hampshire (2001)
New Mexico (2003)
North Carolina (2002)
North Dakota (2000)
Ohio (2004)
Oregon (2002)
Pennsylvania (2002)
Rhode Island (2001)
South Dakota (2001)
Texas mesas (2000)
Utah (2003)
Vermont (2001)
Virginia (2002)
Washington (2002)
West Virginia (2002)
Wyoming (2002)
The remaining states use data from the 1987 "Wind Energy Atlas of the United States".
Transmission Lines Voltage (kV)
345 - 499
500 - 699
700 - 799
1000 (DC)
Source: POWERmap, powermap.platts.com, ©2007 Platts, a division of the McGraw-Hill Companies
Wind Power Classification
Wind Power Class
Resource Potential
Wind Power Density at 50 m W/m²
Wind Speed a at 50 m m/s
Wind Spee at 50 m mph
2 Marginal 200 - 300 5.6 - 6.4 12.5 - 14.3
3 Fair 300 - 400 6.4 - 7.0 14.3 - 15.7
4 Good 400 - 500 7.0 - 7.5 15.7 - 16.8
5 Excellent 500 - 600 7.5 - 8.0 16.8 - 17.9
6 Outstanding 600 - 800 8.0 - 8.8 17.9 - 19.7
7 Superb 800 - 1600 8.8 - 11.1 19.7 - 24.8
a Wind speeds are based on a Weibull k value of 2.0



frequency
energy
hours
MW-hours
wind speed (m/s)
0
100
200
300
400
500
600
700
800
0
5
10
15
20
25

Wind electricity

- 800 GWp as of 2021 (3% global electricity); leading: China (35%), USA (21%, 1/3 in Texas), Germany (6%), India, Spain, UK (4%)
- Common in farms before national grids; now MW turbines
- 25% of electricity in Denmark and Iowa
- Cost-competitive with gas in favorable locations
- Variable on all timescales; now generally balanced by other, dispatchable generation (hydropower and natural gas)

Hydroelectricity

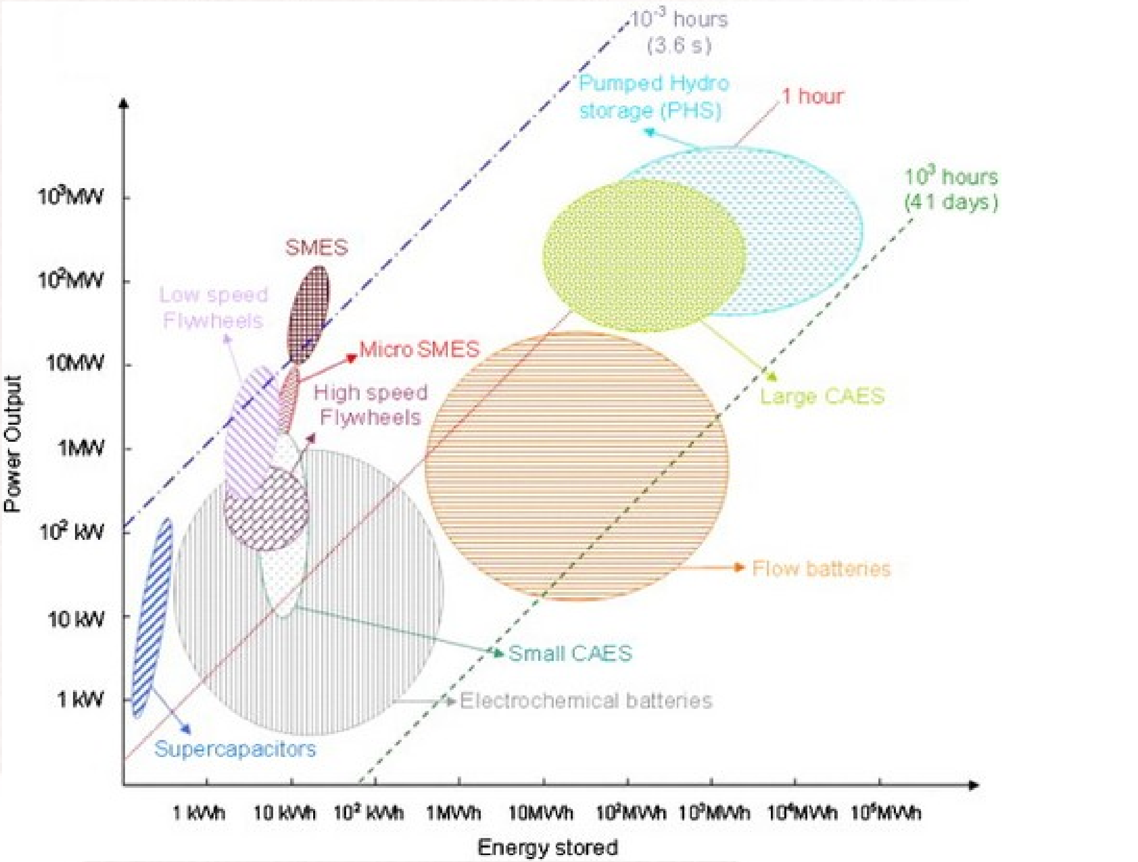
- 980 GWp (16% electricity)
- Cheap at good sites, main source of electricity in some areas
- Highly dispatchable – can be used as needed
- Some ongoing expansion, often flooding large areas (China, Brazil)
- Drought resulting from global warming and reservoir sedimentation may strain sustainability

Biomass

- Some potential to burn as a source of electricity – 20% of total in Finland, 5% in Germany
- Sustainable use level of biomass as fuel remains to be determined, but limited to a small share of current energy demand, ideally for uses that are hard to meet otherwise
- (Deforestation was the reason for turning to coal in the first place)

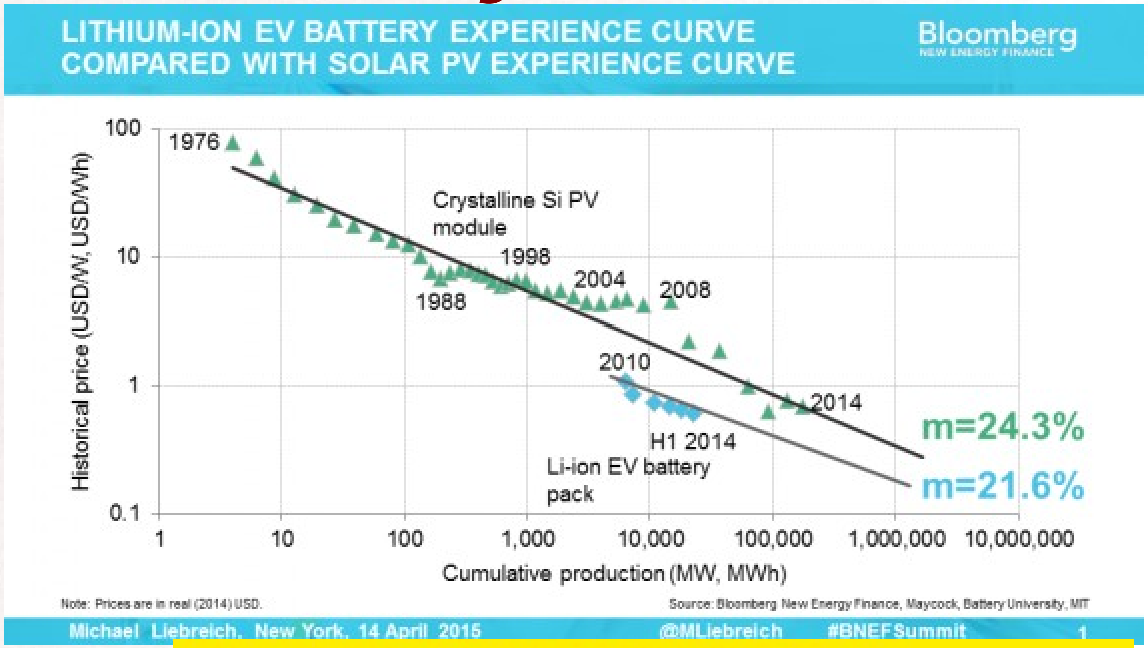
Other storage technologies

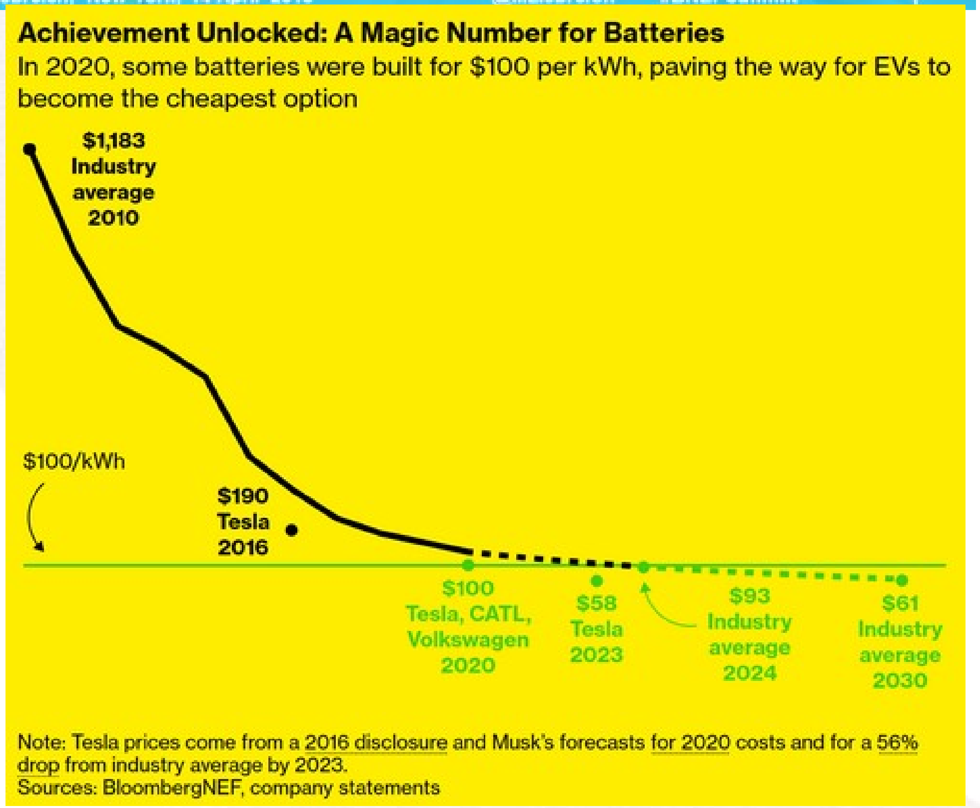
- Batteries (usu. limited number of discharge cycles, expensive at scale)
- Flywheels and capacitors (for short-term power regulation)
- Pumped hydro or brick towers or hydraulic pressure
- Compressed air
- *Mounting interest*



Battery advances

- Cost gradually declining
- Pilot projects in many places: Australia, California, Hawai'i ...
- Li dominates, but interest in cheap materials like Na-S, Fe
- Combine with managing demand and storing heat





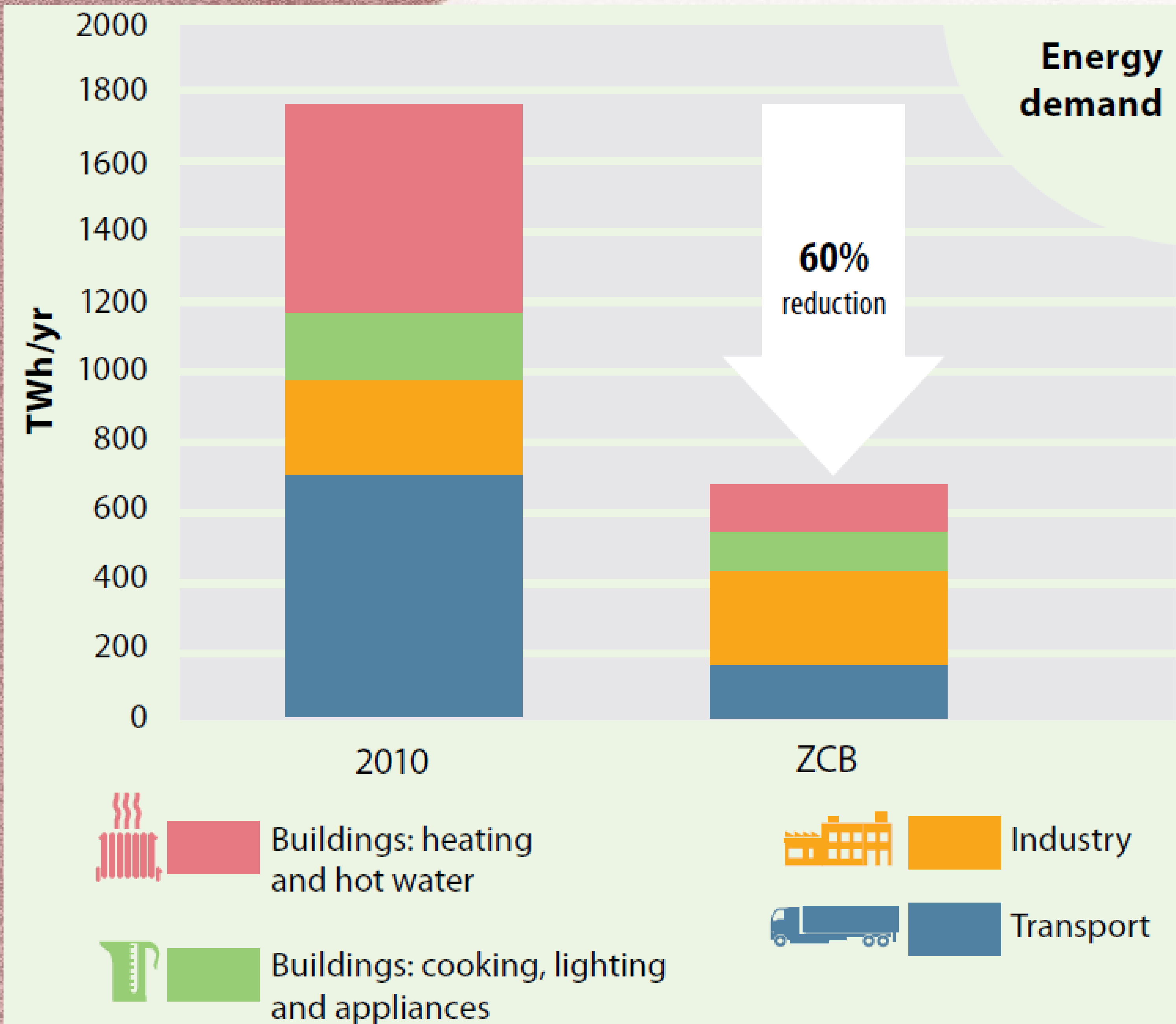
Distributed energy: living off the grid

- Villages, or unreliable central power
- PV, small hydro, perhaps small wind, battery storage
- Economize on electricity: biogas for cooking, solar water heating, passive climate control, composting toilets...

To be discussed later

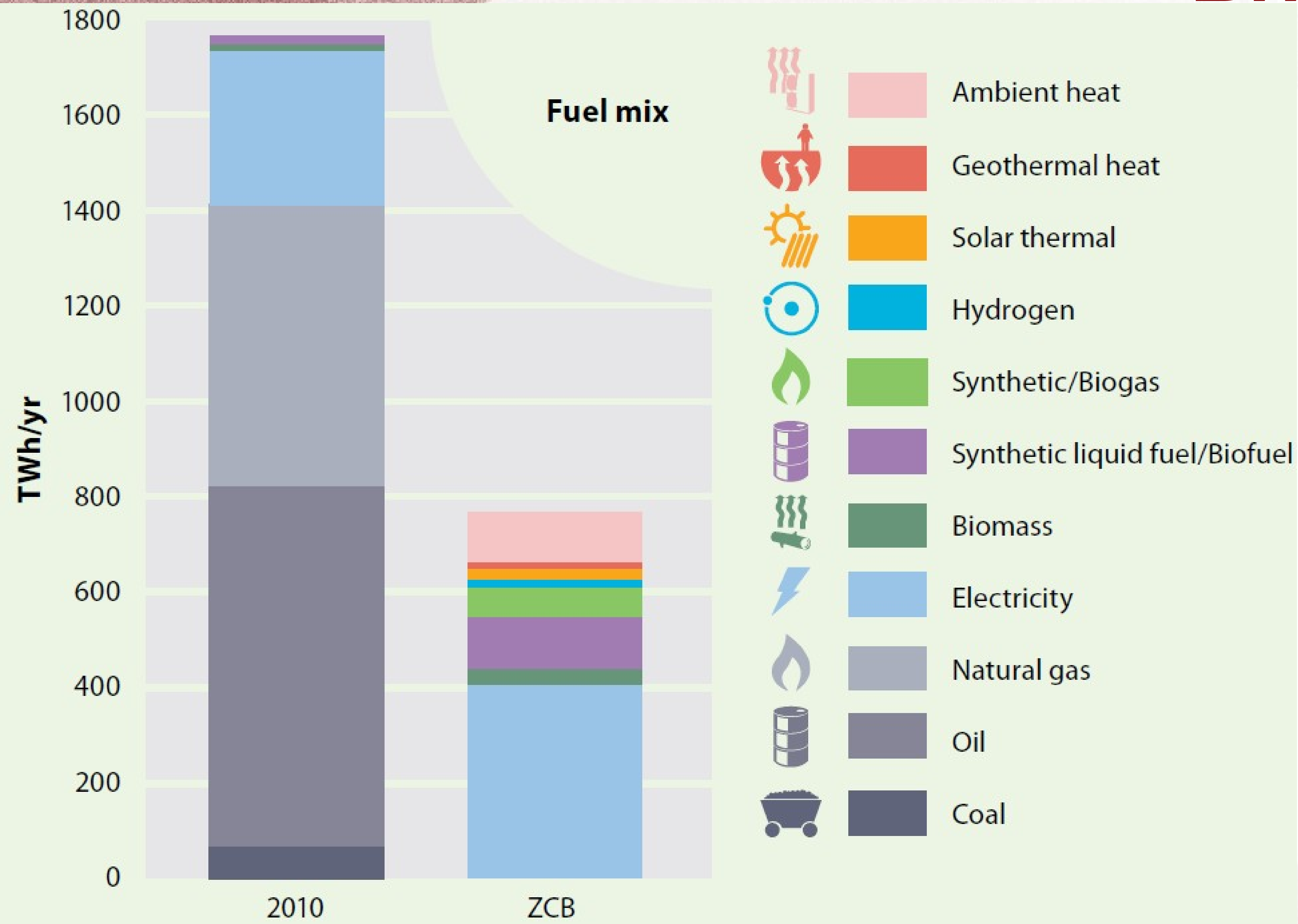
- Transport: Electrification, batteries, liquid biofuels
- Building comfort: solar design, solar water heating, insulation, ...
- Energy for obtaining water and treating wastewater
- Agricultural products and bio-feedstocks

Britain: particularly tough (cf. McKay)



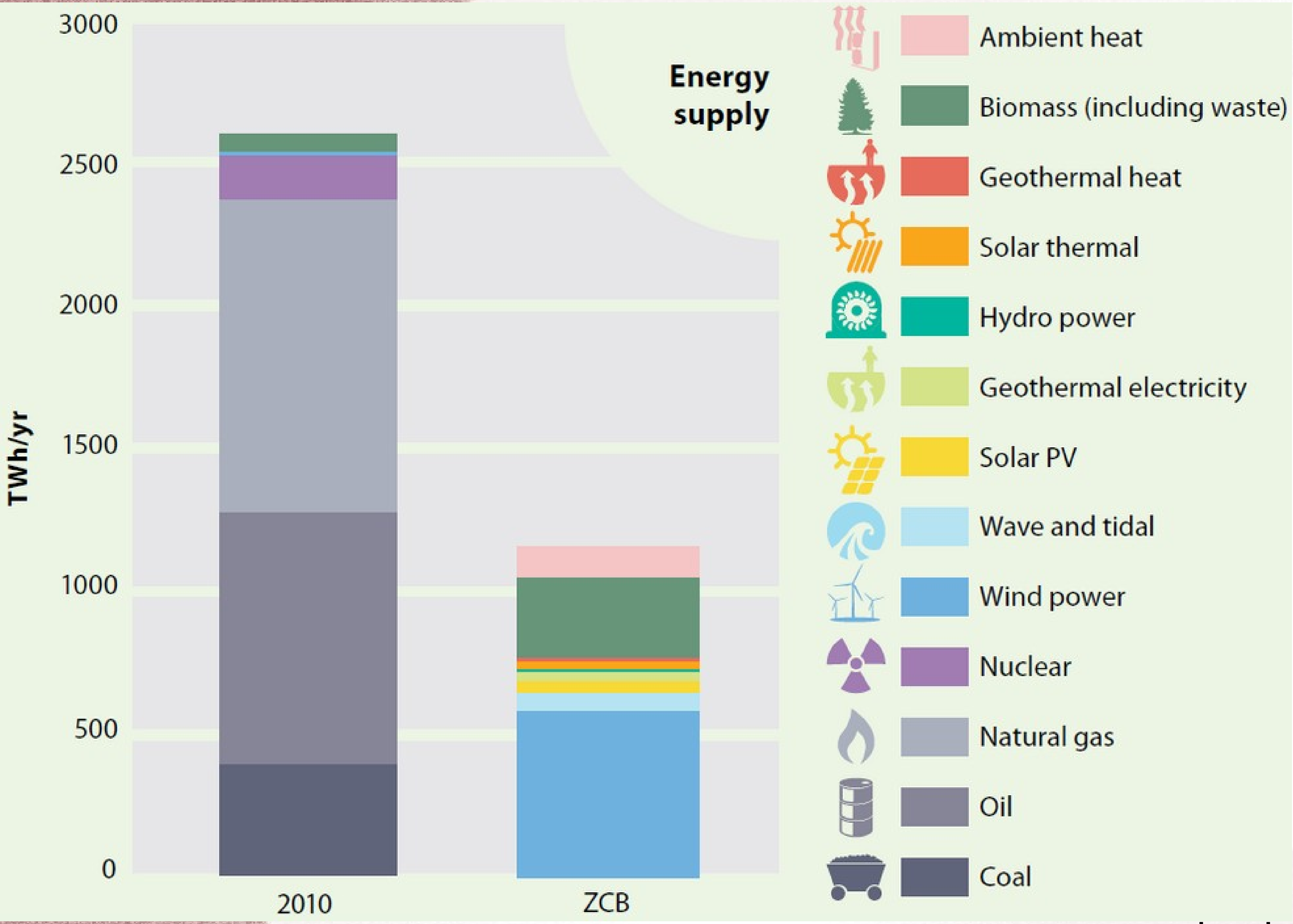
zerocarbonbritain.org

Britain



Fuel mix
TWh/yr
1800
1600
1400
1200
1000
800
600
400
200
0
2010
ZCB
Ambient heat
Geothermal heat
Solar thermal
Hydrogen
Synthetic/Biogas
Synthetic liquid fuel/Biofuel
Biomass
Electricity
Natural gas
Oil
Coal

Britain



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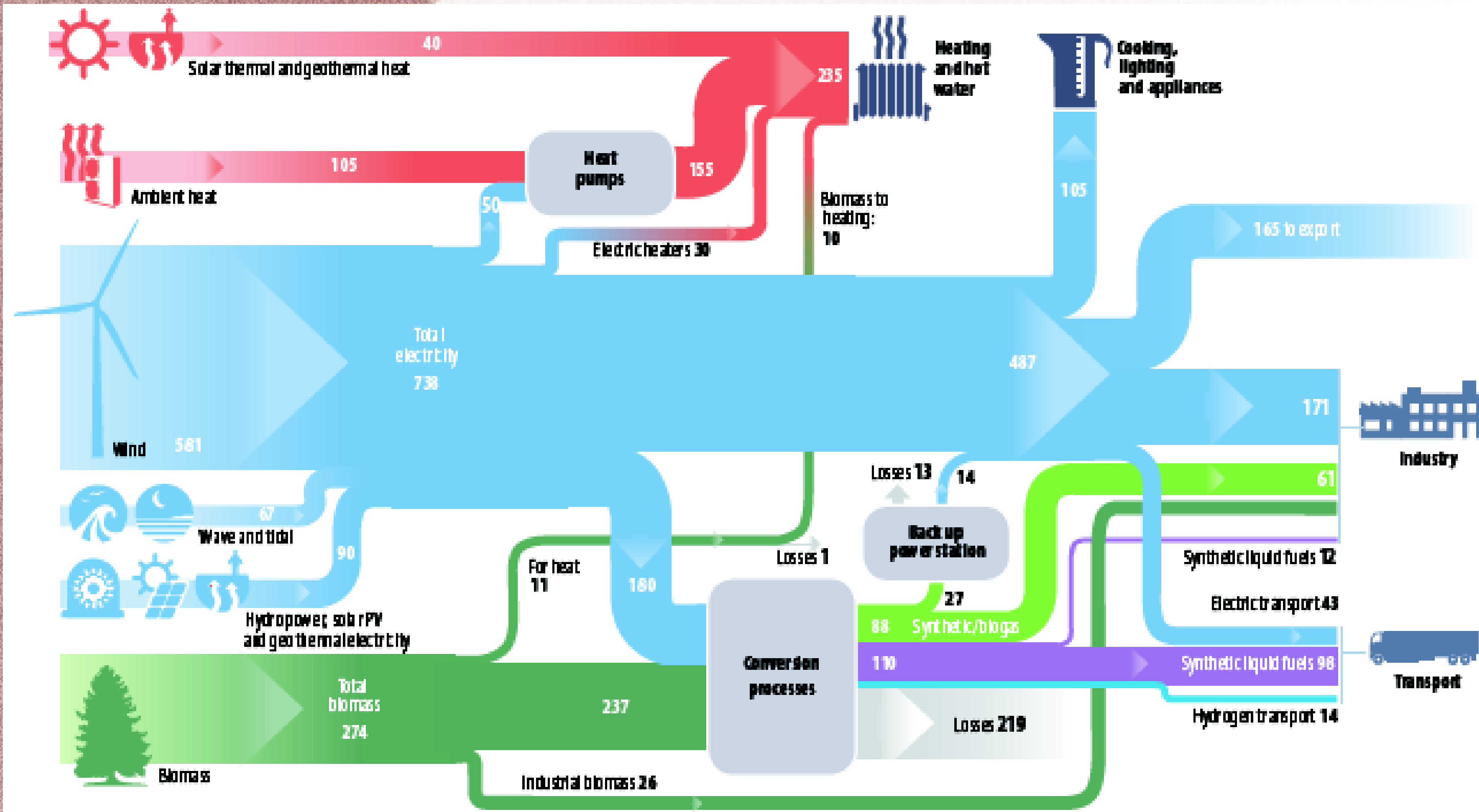
Britain



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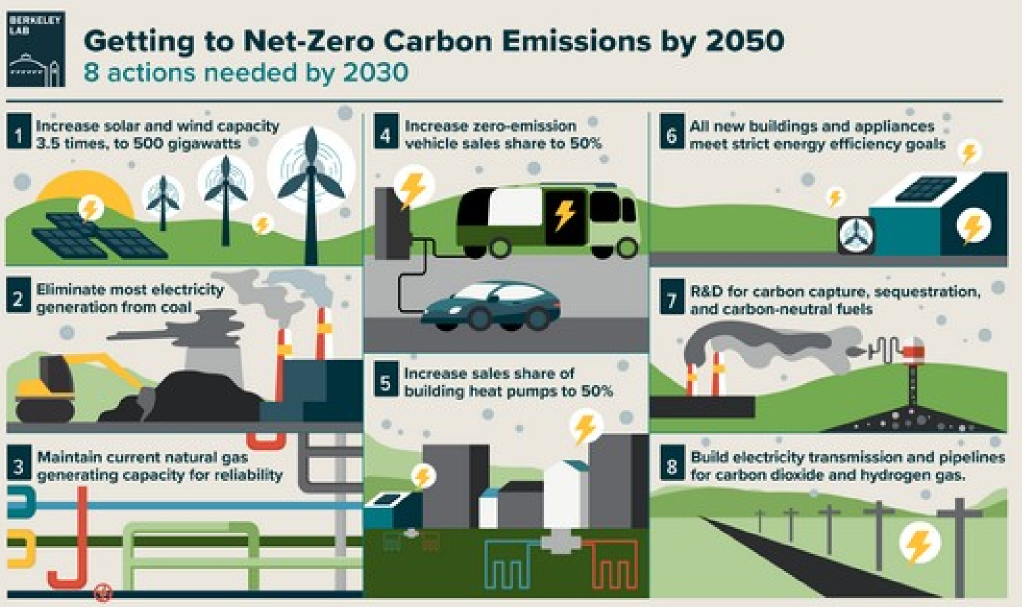
New study: A zero-emissions US is now pretty cheap

In 2050, benefits to the US offset costs, but there are some unexpected outcomes.

JOHN TIMMER - 1/31/2021, 8:00 AM



Carbon-Neutral Pathways for the United States

James H. Williams, Ryan A. Jones, Ben Haley, Gabe Kwok, Jeremy Hargreaves, Jamil Farbes, Margaret S. Torn

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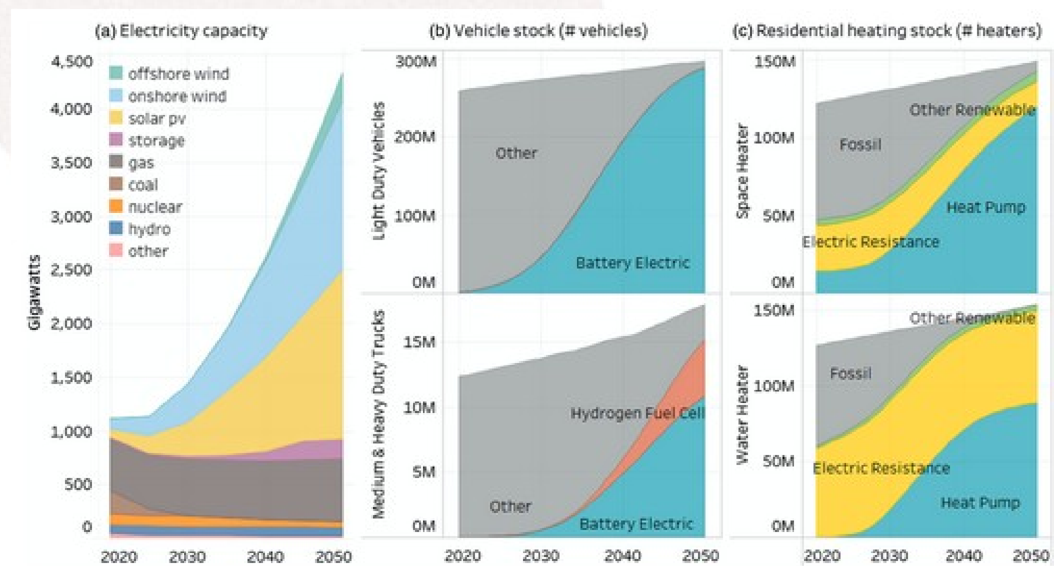

In conclusion

- Big technological and commercial changes underway
- Transitioning from fossil fuels is a big undertaking, but cheap renewables and storage create great opportunities
- Transportation, building, industry energy sectors would need to shift to electricity or use renewable fuel
- Demand can be rethought along with supply
- Policy can help