Physics of Sustainable Energy

Prof. Mark Alford

Fall 2024

What math do you need to know?

- Square roots
- Scientific ("exponential") notation for numbers
- Unit conversions

And, even more importantly,

> How to do *rough estimates*,
> and avoid unnecessary precision.

In our calculations, we only want to get a *roughly right* answer. 20% accuracy is usually good enough. Sometimes we'll only need the answer to be correct to within a factor of 2.

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Q: What's the population of China?

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E.g.,
Q: What's the population of China?
A: about 1.4 billion NOT "1,445,690,926"

Scientific ("exponential") notation

$$
\begin{aligned}
3{,}000{,}000 &= 3 \times 10^{6} & \\
\ldots & & \\
3000 &= 3 \times 10^{3} & \\
300 &= 3 \times 10^{2} & \\
30 &= 3 \times 10^{1} & 10^{1} = 10 \\
3 &= 3 \times 10^{0} & 10^{0} = 1 \\
0.3 &= 3 \times 10^{-1} & 10^{-1} = 0.1 \\
0.03 &= 3 \times 10^{-2} & \\
0.003 &= 3 \times 10^{-3} & \\
\ldots & & \\
3 \text{ millionths} &= 3 \times 10^{-6} &
\end{aligned}
$$

Exercise

What fraction of the population of the USA lives in Missouri?

(A) 2%   (B) 1%   (C) 20%   (D) 10%

Metric prefixes

G	giga	billion	10^9	$1\,\mathrm{GW} = 10^9\,\mathrm{W}$
				1 giga-Watt = a billion Watts
M	mega	million	$1{,}000{,}000 = 10^6$	$1\,\mathrm{MT} = 10^6\,\mathrm{T}$
				1 mega-Tonne = a million Tonnes
k	kilo	thousand	$1{,}000 = 10^3$	$1\,\mathrm{kg} = 1000\ \mathrm{g}$
c	centi	hundredth	$0.01 = \frac{1}{100} = 10^{-2}$	$1\,\mathrm{cm} = 0.01\,\mathrm{m}$
m	milli	thousandth	$0.001 = \frac{1}{1000} = 10^{-3}$	$1\,\mathrm{mm} = 0.001\,\mathrm{m}$
μ	micro	millionth	$\frac{1}{1{,}000{,}000} = 10^{-6}$	$1\,\mu\mathrm{m} = 10^{-6}\,\mathrm{m}$
n	nano	billionth	10^{-9}	$1\,\mathrm{nm} = 10^{-9}\,\mathrm{m}$

Unit conversions

See course videos:

- Unit Conversions 1: basic technique
- Unit Conversions 2: multiple units

Exercise

One yard is 3 feet. What is one square yard, expressed in square feet?
(A) $1\,\mathrm{ft}^2$ (B) $3\,\mathrm{ft}^2$ (C) $9\,\mathrm{ft}^2$ (D) $0.33\,\mathrm{ft}^2$

The area of Missouri is 70,000 square miles. What is that in square kilometers?
(A) $70,000\,\mathrm{km}^2$ (B) $180,000\,\mathrm{km}^2$
(C) $122,000\,\mathrm{km}^2$ (D) $44,000\,\mathrm{km}^2$

Unit conversion toolkit, part 1

Start building your unit conversion toolkit:

Length:	1 mi = 1.6 km	1 inch = 2.5 cm	1 foot = 30 cm	...

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Exercise

What is 1 cup in milliliters?

(A) 50 ml (B) 380 ml (C) 250 ml (D) 120 ml

Exercise

How many liters are there in a cubic meter?

(A) 100 (B) 1000 (C) 10,000 (D) 1 million

Unit conversion toolkit, part 2

Mass: $1\,\text{lb} = 16\,\text{oz}$

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Mass:	$1\,\text{lb} = 16\,\text{oz}$	$1\,\text{kg} = 2.2\,\text{lb}$ $\approx 2\,\text{lb}$	$1\,\text{ton} \approx 1000\,\text{kg}$	...

Exercise

Roughly how many pounds in a ton?

(A) 100 (B) 200 (C) 1000 (D) 2000

Density

Density of water is $1\,\frac{\text{kg}}{\text{liter}} = 1\,\frac{\text{g}}{\text{ml}} = 1\,\frac{\text{g}}{\text{cm}^3}$

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Exercise

What is the mass of a cubic meter of water?

(A) 1 kg (B) 100 kg (C) 1 ton (D) 100 ton

Energy as "Money"

Energy is like Money.

> The amount of energy you have available determines what you can get done.

Energy and Money are both *conserved*: they can be transferred between different places and take different forms, but the total amount is unchanged.

Except that governments can "print money".

- How do we obtain energy from our environment?

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- How do we use energy to get things done?

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- How do we use energy to get things done?
  Engines, Motors, Muscles, Light bulbs, Speakers. . .

Energy Topics

- Forms of energy
  Kinetic, Chemical, Nuclear, Electrical, Thermal
- Quantifying amounts of energy
  Units: Calories, kiloWatt-hours, etc
- Storing energy
  Batteries, Food, Fuels, Uranium... Which is "best"?
- **Application:** comparison of electric cars, hybrid cars, and gasoline cars
- Cost of energy
  Coal, Gas, Oil, Electricity, etc
- Power: rate of flow of energy

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Energy is taken in or given out during a change of state

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- Energy stored in wires that are carrying an electric current

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- Energy stored as heat, released when hot object cools
  (hotter $\rightarrow$ cooler) (Thermal Energy)

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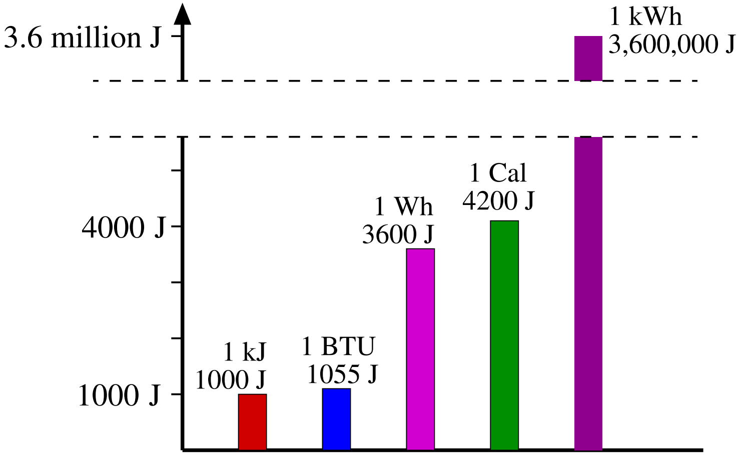
kiloWatt-hour (kWh)	$= 3.6 \times 10^6$ J	energy used by a 1 kW appliance running for 1 hr Electricity from a utility typically costs about 10 ¢/kWh

Energy units: visual comparison



Unit conversion toolkit, part 3

Add Energy conversions to the toolkit:

Length:	1 mi = 1.6 km	1 inch = 2.5 cm	1 foot = 30 cm	...
Volume:	1 liter = 10^3 cm^3 1 ml = 1 cm^3	1 Gal = 4 quarts 1 quart = 4 cups	1 Gal = 3.8 liters ≈ 4 liters	...
Mass:	1 lb = 16 oz	1 kg = 2.2 lb ≈ 2 lb	1 ton ≈ 1000 kg	...
Energy:	1 Cal = 4200 J 1 BTU = 1055 J	1 Wh = 3600 J ...	1 kWh = 3.6×10^6 J	

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Mass:	$1\,\text{lb} = 16\,\text{oz}$	$1\,\text{kg} = 2.2\,\text{lb}$ $\approx 2\,\text{lb}$	$1\,\text{ton} \approx 1000\,\text{kg}$	...
Energy:	$1\,\text{Cal} = 4200\,\text{J}$ $1\,\text{BTU} = 1055\,\text{J}$	$1\,\text{Wh} = 3600\,\text{J}$ ...	$1\,\text{kWh} = 3.6 \times 10^6\,\text{J}$	

Exercise

What is 1 kiloWatt-hour in Calories?

(A) 860 Cal (B) 4200 Cal (C) 3600 Cal (D) 3.6 Cal

Energy Storage: requirements

Energy Storage: requirements

We have two requirements which sometimes conflict:

- Accessibility: energy can easily be extracted from “container” and used.
- High energy density: lots of energy stored per gram of “container”.

Energy storage table

Storage medium	$\frac{\text{Calories}}{\text{gram}}$	$\frac{\text{Joules}}{\text{gram}}$	change of state to extract energy
Flywheel	0.01–0.1	50–500	moving $\rightarrow$ stationary

Energy storage table

Storage medium	Calories / gram	Joules / gram	change of state to extract energy
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Battery lead-acid, car	0.03	140	charged → discharged
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Battery (lithium-ion, computer, elec car)	0.05 – 0.2 typical: 0.1	200 – 800 typical: 400	charged → discharged
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Tri-nitro toluene (TNT explosive)	1	4200	TNT $\rightarrow$ N_2, H_2, CO
Carbohydrates, protein	4	17,000	$+ O_2 \rightarrow CO_2 + H_2O$
Coal	6	27,000	$+ O_2 \rightarrow CO_2$
Alcohol (ethanol, methanol)	6	27,000	$+ O_2 \rightarrow CO_2 + H_2O$
Butter	7	29,000	$+ O_2 \rightarrow CO_2 + H_2O$
Fat	9	38,000	$+ O_2 \rightarrow CO_2 + H_2O$
Gasoline	10	42,000	$+ O_2 \rightarrow CO_2 + H_2O$
Natural gas (methane = CH_4)	13	54,000	$+ O_2 \rightarrow CO_2 + H_2O$

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Hydrogen (gas or liquid)	26	110,000	$+ O_2 \rightarrow H_2O$
Uranium-235	20 million	83 billion	$^{235}U \rightarrow$ 2 smaller nuclei

Electric car vs Gasoline car, generalities

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(1) Range
(2) Cost per mile

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Energy Usage:
Gasoline engines are $\sim$ 20% efficient,
electric motors are $\sim$ 80% efficient

Electric motor is 4 times more efficient than gasoline engine.

Electric car vs Gasoline car, specifics

(1) Range: How far can we go on:

- *Gasoline car:* Full tank of gasoline
- *Electric car with Lithium-ion batteries:* Fully charged battery pack

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- *Electric car:* $\frac{\text{Cost}}{\text{kWh of energy in battery}} \times \frac{\text{kWh of energy in battery}}{\text{Miles traveled}}$

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Other issues:

- Cost of vehicle, including battery pack
- Upkeep costs

Exercises

How far can an electric car travel if it has a fully charged Li-ion battery weighing 100 lb ?

(A) 1 mile (B) 4 miles (C) 12 miles (D) 30 miles

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How many kWh of energy are there in a gallon of gasoline?

(A) 35 kWh (B) 15 kWh (C) 3 kWh (D) 7 kWh

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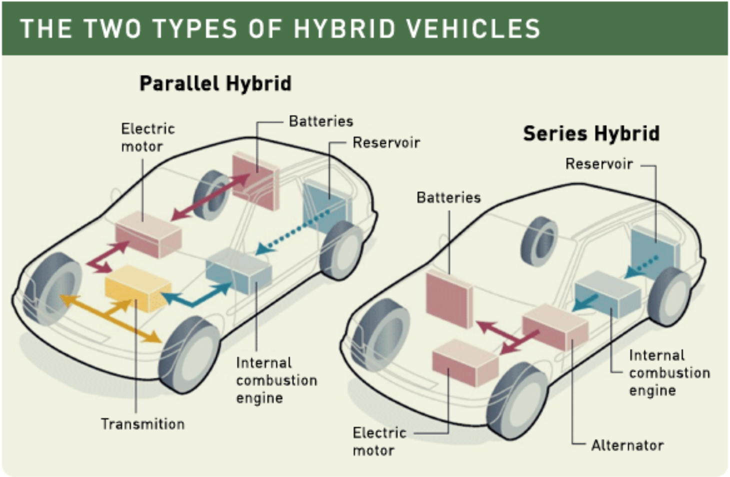
What is the cost of each kWh of energy in gasoline?

(A) 3¢ (B) 10¢ (C) 30¢ (D) $ 1

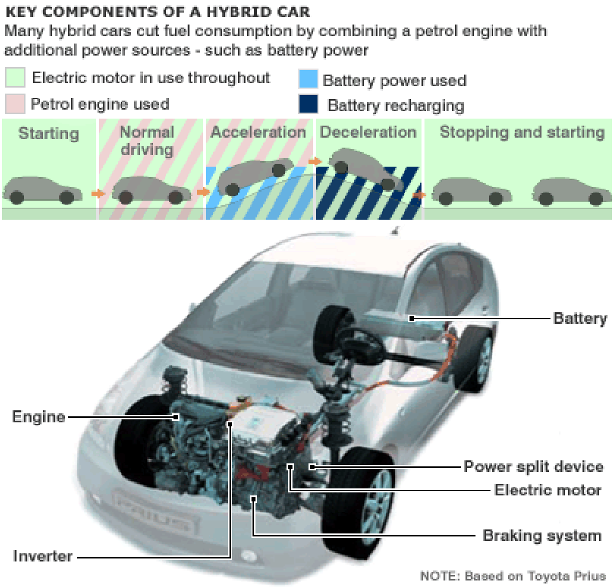
Research mini-project: Hybrid Cars

1. How does a typical ("series") hybrid car work?
2. What is the sequence of energy transformations that occurs?
3. What makes a hybrid car more efficient than a regular gasoline car?

Types of Hybrid Car



Operation of Hybrid Car



Hybrid Car: summary

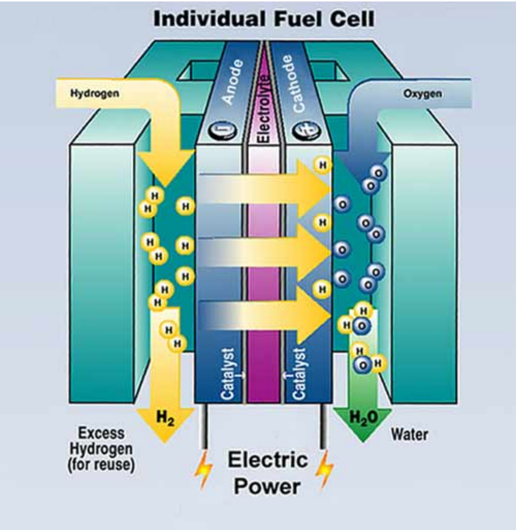
A hybrid car is a gasoline powered electrically driven car that achieves higher fuel efficiency.

- The small gasoline engine is just big enough to run the car at normal speed.
- The engine generates electricity via an alternator. The electricity powers electric motors to drive the wheels.
- For acceleration, the battery supplies extra power.

Why is a hybrid car more efficient than a regular gasoline car?

- Engine can be tuned to higher efficiency, about 35%, because it can run at a constant rate independent of the speed of the car
- Regenerative braking recaptures the car's kinetic energy so it can be used again.

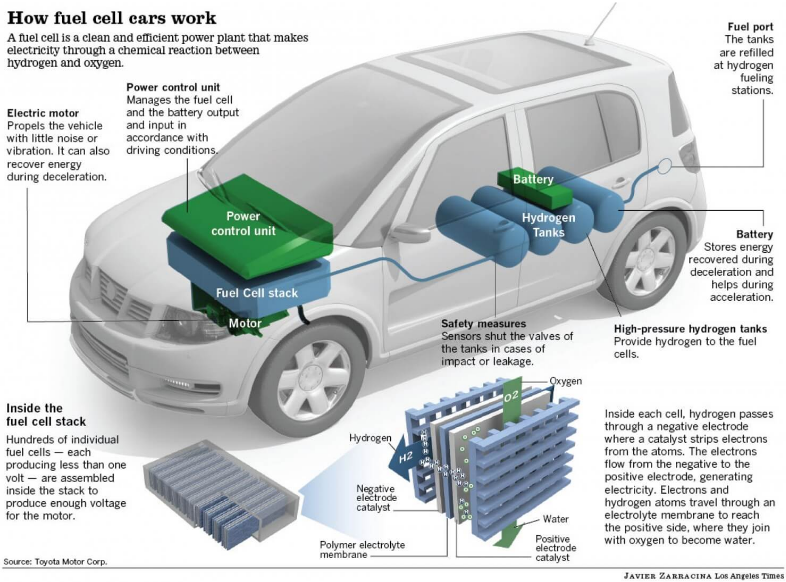
Hydrogen Fuel Cell



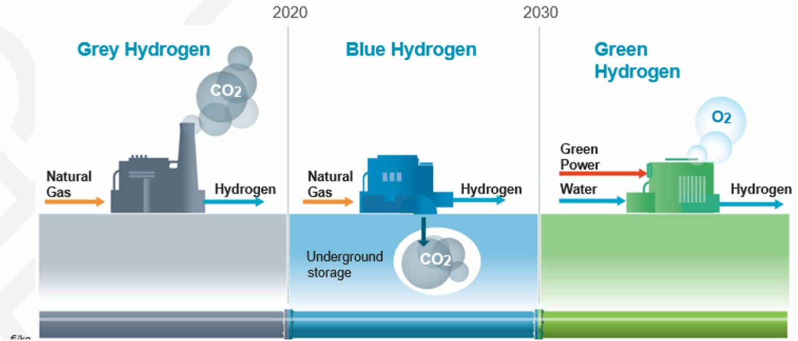
Fuel cell "burns" Hydrogen to make electricity. So we can use Hydrogen as a fuel, i.e. a way to store and transport energy.

Actual Hydrogen fuel cell

Hydrogen fuel cell car



Types of hydrogen



Energy per unit volume

Gasoline vs hydrogen

	energy per gram		density g/ml		energy per ml
Gasoline:	$10\,\frac{\text{Cal}}{\text{g}}$	$\times$	$0.75\,\frac{\text{g}}{\text{ml}}$	$\approx$	$7\,\frac{\text{Cal}}{\text{ml}}$
Compressed Hydrogen gas	$26\,\frac{\text{Cal}}{\text{g}}$	$\times$	$0.023\,\frac{\text{g}}{\text{ml}}$	$\approx$	$0.6\,\frac{\text{Cal}}{\text{ml}}$
Liquid Hydrogen	$26\,\frac{\text{Cal}}{\text{g}}$	$\times$	$0.07\,\frac{\text{g}}{\text{ml}}$	$\approx$	$2\,\frac{\text{Cal}}{\text{ml}}$

Compressed hydrogen gas is kept at $\sim$ 700 atmospheres in pressurized cylinders.
Liquid hydrogen must be kept at 20 K = -250 C = -420 F

Exercise

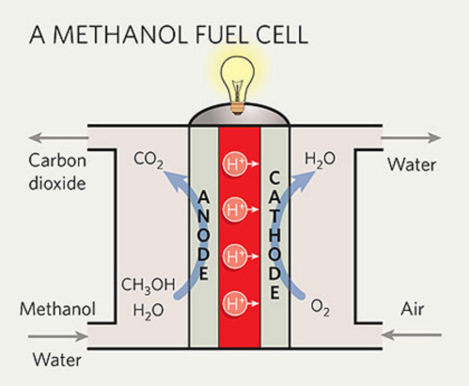
Estimate how large the fuel tank of a liquid-hydrogen-fueled car would have to be if it can go 300 miles on one tankful.
Take into account the efficiencies of gas engines, fuel cells, electric motors.

A: three times bigger than a gasoline car's tank
B: three times smaller than a gasoline car's tank
C: nine times bigger than a gasoline car's tank
D: about the same as a gasoline car's tank

Methanol Fuel

Instead of Hydrogen, one can store energy in the form of methanol.

- Can be made easily from fossil fuels or biomass (not yet wind/solar)
- Liquid fuel: easy to handle
- Energy density is about half that of gasoline
- Unlike ethanol/gasoline, methanol can be used via a fuel cell (as well as via the less-efficient internal combustion engine)



Methanol Fuel Cell Car

Marginal Cost of Energy

Marginal Cost = cost per kWh once generator is in place

Fuel	Market cost	Cost per kWh of heat	Cost per kWh of electricity from power plant
Wholesale Fuels:			
Coal	\$60/ton	0.75¢	2.5¢
Natural gas	\$2 per million BTU	0.7¢	2¢
Oil	\$85 per barrel	4¢	12¢

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Retail Fuels:			
Natural Gas	\$15 per 10^3 cubic feet	5¢	
Gasoline	\$3.50 per gallon	10¢	
Electricity	\$0.10 per kWh	10¢	10¢

Marginal Cost of Energy

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Retail Fuels:			
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Gasoline	\$3.50 per gallon	10¢	
Electricity	\$0.10 per kWh	10¢	10¢

Exercise

How much coal does it take to generate 1 kWh of electricity?

(A) 100 lb (B) 5 kg (C) 1 lb (D) 50 g

Levelized Cost of Energy (LCOE)

For electricity generation, covering whole lifetime of the generator: construction, operation, decommissioning

$$\text{LCOE} = \text{Average Cost} = \frac{(\text{total amount spent in ¢})}{(\text{total energy generated in kWh})}$$

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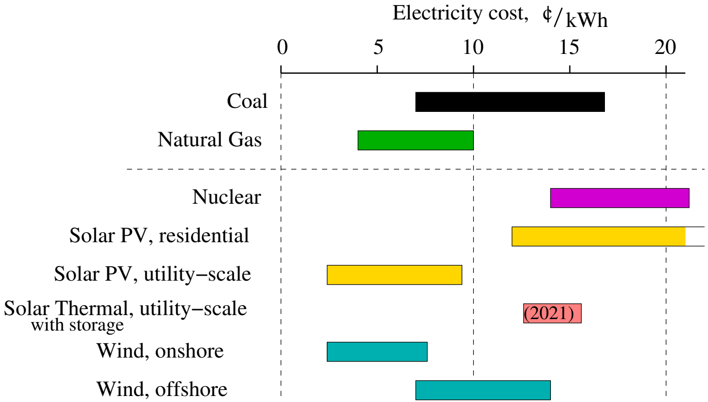

Lazard Cost of Energy Analysis, 2023

Understanding Power vs Energy

$$\text{Power} = \text{Rate of Energy Transfer}$$

$$\text{Power} = \frac{\text{Energy}}{\text{Time}}$$

So they have different units:

Energy units:

Joules, Calories, etc.

Power units:

$\frac{\text{Joules}}{\text{sec}}$ (Watts), $\frac{\text{Calories}}{\text{day}}$, $\frac{\text{quads}}{\text{year}}$, etc.

Money analogy:

Energy is like money, e.g.

One AA battery stores 10,000 J of energy

My bank account holds $10,000

Power is like income (rate of expenditure), e.g.

A Playstation uses 100 W = 100 J/s of power

My part-time job pays me $100 per day.

Examples of power consumption

Power	examples
$1\,\mathrm{W} = 1\,\mathrm{J s^{-1}}$	night light; small flashlight
$100\,\mathrm{W}$	

Examples of power consumption

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$75\,\mathrm{kW} = 100\,\mathrm{hp}$	

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$3\,\text{TW} = 100\,\frac{\text{quad}}{\text{year}}$	U.S. total power consumption
$17\,\text{TW} = 580\,\frac{\text{quad}}{\text{year}}$	Global total power consumption

Exercise

A Playstation 4 uses about 100 W of power. How long would it have to run in order to consume 1 kWh of electricity?

(A) 6 minutes (B) 10 minutes (C) 6 hours (D) 10 hours

U.S. annual energy consumption

- What are the main things we use energy for?

U.S. annual energy consumption

- What are the main things we use energy for?
  - Transportation: need high-density easily rechargeable storage, e.g. liquid fuel or good battery
  - Heating
  - Electricity: lighting, cooling, appliances, etc
- What are our main sources of energy?

U.S. annual energy consumption

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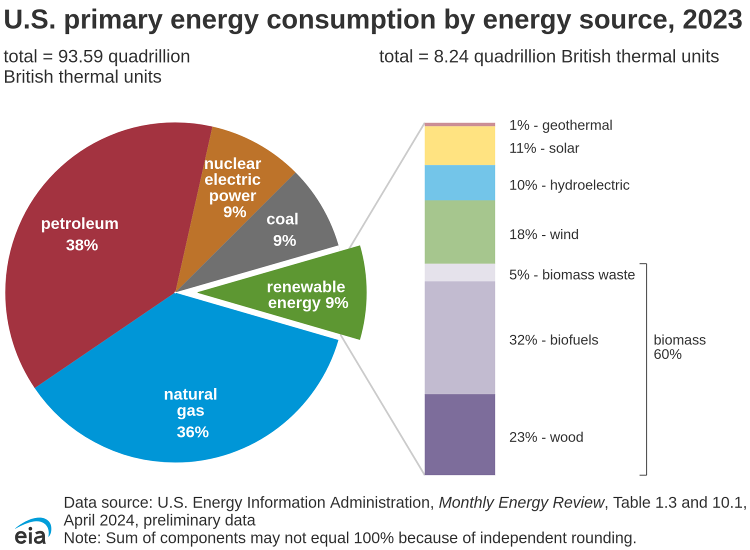
  - Transportation: need high-density easily rechargeable storage, e.g. liquid fuel or good battery
  - Heating
  - Electricity: lighting, cooling, appliances, etc
- What are our main sources of energy?
  Oil, Natural Gas, Coal, Nuclear, Renewables . . .

U.S. annual energy consumption



U.S. Energy Information Administration

Exercise

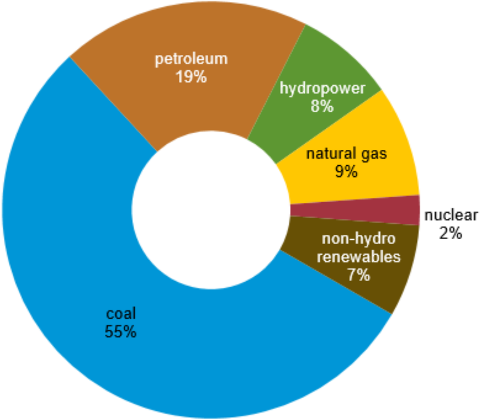
The U.S. consumes 100 quad/yr. What is the U.S.'s average rate of power consumption per person?

(A) 1 kW/person
(B) 1 MW/person
(C) 100 kW/person
(D) 10 kW/person

China annual energy consumption

Total=158 quads

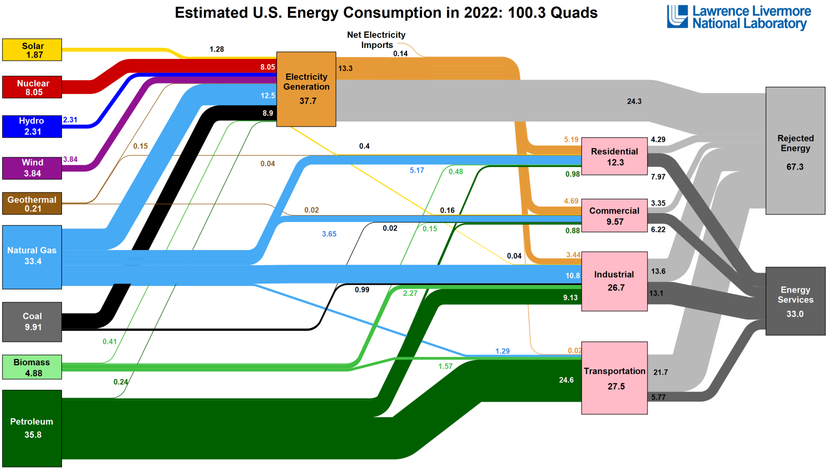
Figure 1. Total primary energy consumption in China by fuel type, 2021



Data source: BP Statistical Review of World Energy 2022
Note: Total may not equal 100% because of independent rounding. Includes only commercial fuel sources and does not account for biomass used outside of power generation.

U.S. annual energy consumption and use

Estimated U.S. Energy Consumption in 2022: 100.3 Quads



Source: LLNL July, 2023. Data is based on DOE/EIA SEDS (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 0.65% for the residential sector, 0.65% for the commercial sector, 0.49% for the industrial sector, and 0.21% for the transportation sector. Totals may not equal sum of components due to independent Rounding. LLNL-MI-410527

Heat: some questions

- What is the difference between heat and temperature?
- Scientists predict that global warming could cause sea levels to rise by several feet, *even if no ice melts*. Why?
- If you run a refrigerator with the door open, will the room get colder or warmer?
- Burning fuel to provide heat is almost 100% efficient. But there are heating methods that are *more than* 100% efficient, such as heat pumps. How do they work?

What is heat?

Heat is a form of energy.

Definition: Heat Energy is Kinetic Energy of randomly moving molecules

Kinetic energy

Energy needed to get a mass M to move at speed v is

$$\underset{[\mathrm{J}]}{E} = \frac{1}{2}\,\underset{[\mathrm{kg}]}{M}\;\underset{[\mathrm{m}^2\,\mathrm{s}^{-2}]}{v^2}$$

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So if you think of movement as a way of storing energy, the energy stored per unit mass is

$$\frac{E}{M} = \tfrac{1}{2} v^2 \quad [\mathrm{J\,kg^{-1}}]$$

Exercise

Estimate the kinetic energy of a car traveling at 50 mi/hr.

(A) 300,000 J
(B) 3000 J
(C) 3 MJ
(D) 30,000 J

Exercise

Estimate the kinetic energy of a car traveling at 50 mi/hr.

(A) 300,000 J
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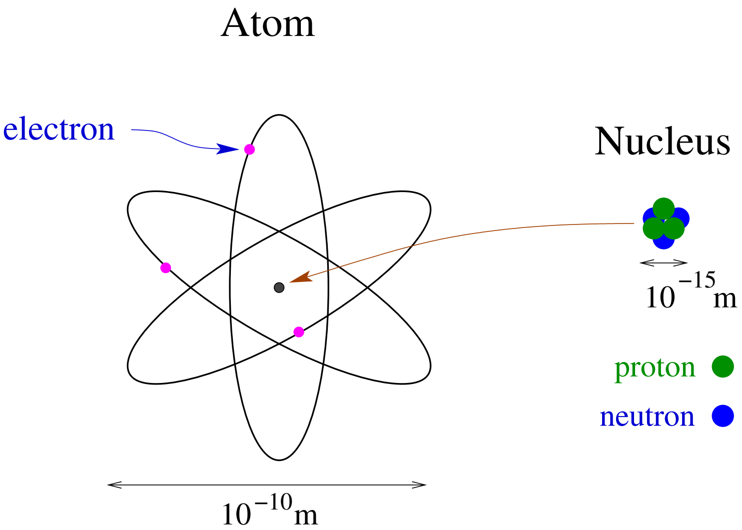
(D) 30,000 J

Roughly how much gasoline did the car need to burn to provide that much kinetic energy?
(A) two teaspoons (10 ml)
(B) a cupful (200 ml)
(C) an egg-ful (50 ml)
(D) a pint (500 ml)

Atom and nucleus



Subatomic particles

Name	Symbol	Charge	Mass
proton	p	$+e$	$1.7 \times 10^{-27}\,\mathrm{kg}$
neutron	n	0	$1.7 \times 10^{-27}\,\mathrm{kg}$
electron	e^-	$-e$	$9.1 \times 10^{-31}\,\mathrm{kg}$ (2000 times lighter!)

Properties of an atom:

Z "atomic number" = no. of protons
= no. of electrons

A "atomic mass number" = (no. of protons) + (no. of neutrons)

Mass comes mostly from the protons and neutrons (electrons are light)

$$\text{Mass of an atom} = \underbrace{(1.7 \times 10^{-27}\,\mathrm{kg})}_{m_N} \times A$$

m_N is the mass of a *nucleon* (proton or neutron).

Periodic Table of the Elements

1 H 1.00794																1 H 1.00794	2 He 4.002602
3 Li 6.941	4 Be 9.012182											5 B 10.811	6 C 12.0107	7 N 14.00674	8 O 15.9994	9 F 18.9984032	10 Ne 20.1797
11 Na 22.989770	12 Mg 24.3050											13 Al 26.981538	14 Si 28.0855	15 P 30.973761	16 S 32.066	17 Cl 35.4527	18 Ar 39.948
19 K 39.0983	20 Ca 40.078	21 Sc 44.955910	22 Ti 47.867	23 V 50.9415	24 Cr 51.9961	25 Mn 54.938049	26 Fe 55.845	27 Co 58.933200	28 Ni 58.6934	29 Cu 63.546	30 Zn 65.39	31 Ga 69.723	32 Ge 72.61	33 As 74.92160	34 Se 78.96	35 Br 79.904	36 Kr 83.80
37 Rb 85.4678	38 Sr 87.62	39 Y 88.90585	40 Zr 91.224	41 Nb 92.90638	42 Mo 95.94	43 Tc (98)	44 Ru 101.07	45 Rh 102.90550	46 Pd 106.42	47 Ag 107.8682	48 Cd 112.411	49 In 114.818	50 Sn 118.710	51 Sb 121.760	52 Te 127.60	53 I 126.90447	54 Xe 131.29
55 Cs 132.90545	56 Ba 137.327	57 La 138.9055	72 Hf 178.49	73 Ta 180.9479	74 W 183.84	75 Re 186.207	76 Os 190.23	77 Ir 192.217	78 Pt 195.078	79 Au 196.96655	80 Hg 200.59	81 Tl 204.3833	82 Pb 207.2	83 Bi 208.98038	84 Po (209)	85 At (210)	86 Rn (222)
87 Fr (223)	88 Ra (226)	89 Ac (227)	104 Rf (261)	105 Db (262)	106 Sg (263)	107 Bh (262)	108 Hs (265)	109 Mt (266)	110 (269)	111 (272)	112 (277)		114 (289) (287)		116 (289)		118 (293)

58 Ce 140.116	59 Pr 140.90765	60 Nd 144.24	61 Pm (145)	62 Sm 150.36	63 Eu 151.964	64 Gd 157.25	65 Tb 158.92534	66 Dy 162.50	67 Ho 164.93032	68 Er 167.26	69 Tm 168.93421	70 Yb 173.04	71 Lu 174.967
90 Th 232.0381	91 Pa 231.03588	92 U 238.0289	93 Np (237)	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (262)

S.E. Van Bramer, 7/22/99

1995 IUPAC masses and Approved Names from http://www.chem.qmw.ac.uk/iupac/AtWt/

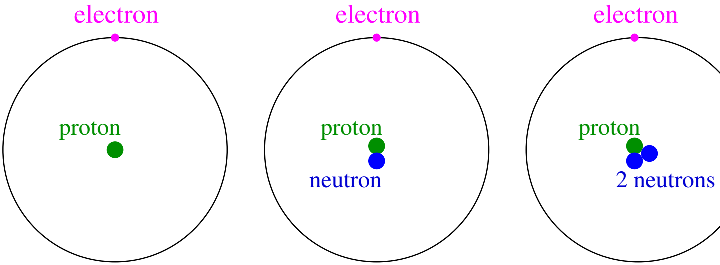
masses for 107-111 from C&EN, March 13, 1995, P 35

112 from http://www.gsi.de/z112e.html

114 from C&EN July 19, 1999

116 and 118 from http://www.lbl.gov/Science-Articles/Archive/elements-116-118.html

Isotopes of hydrogen



^{1}H	^{2}H "Deuterium"	^{3}H "Tritium"
$Z = 1$	$Z = 1$	$Z = 1$
$A = 1$	$A = 2$	$A = 3$

Exercise

How many water molecules are there in a liter of water?

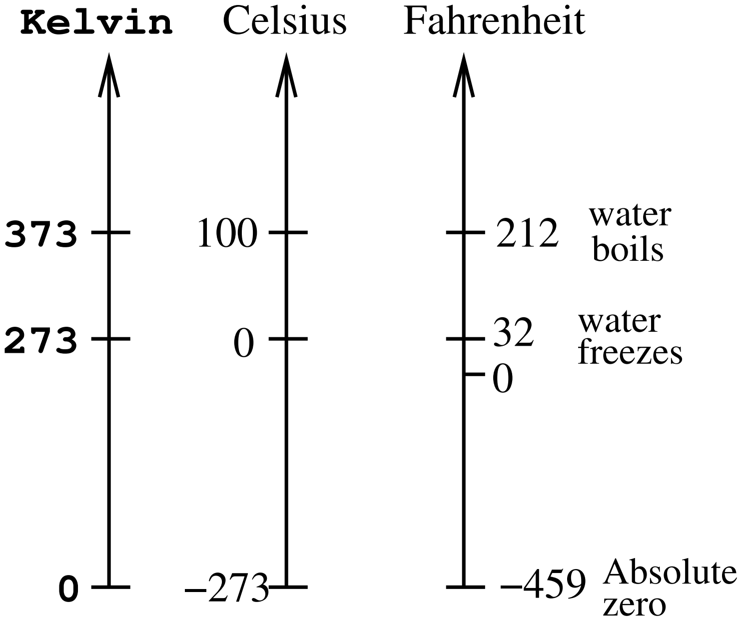
(A) 5×10^{26}
(B) 3×10^{25}
(C) 2×10^{24}
(D) 6×10^{23}

Temperature

The *temperature* of something is a measure of how much disordered kinetic energy each molecule has.

$$\underbrace{\mathcal{E}}_{\text{KE/molecule (J)}} \approx \underbrace{2 \times 10^{-23}\ \text{J/K}}_{\text{Boltzmann const}} \times \underbrace{T_{\text{K}}}_{\substack{\text{Temperature} \\ \text{in } \textbf{Kelvin}}}$$

Temperature scales



Exercise

How much thermal energy is there in a liter of water at room temperature?

(A) 2 J
(B) 20 J
(C) 2000 J
(D) 200,000 J

Exercise

Suppose you have a mercury filling in one of your teeth.

Which is moving faster, the mercury atoms in the filling or the water molecules in your body?

Exercise

A steel bridge is 1km long. How much does its length change by from mid-winter to mid-summer?

(A) 0.03 cm
(B) 0.3 cm
(C) 3 cm
(D) 30 cm

Thermal Expansion: railroads

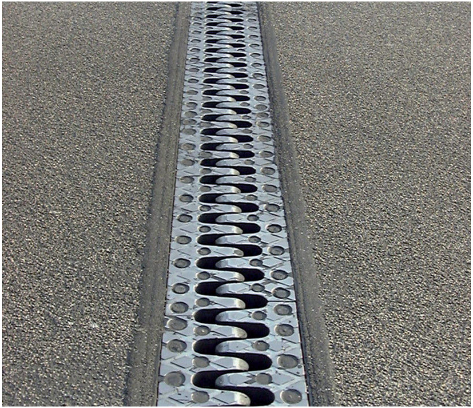
Expansion joints

Expansion joints are provided in running rails to allow for temperature changes. The additional rails in the centre of the track are bolted to the sleepers to prevent the sleepers being shifted by rail expansion.

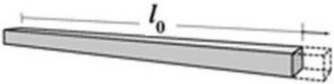
Without expansion joints

Thermal Expansion: bridges

Bridge expansion joint



Thermal Expansion formulas



$$\Delta l = \alpha\, l_0\, \Delta T$$

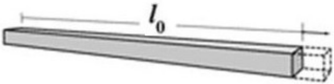
Δl = change in length

α = coefficient of linear expansion

l_0 = original length

ΔT = change in temperature

Thermal Expansion formulas



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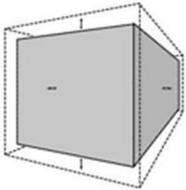

$$\Delta V = 3\alpha\, V_0\, \Delta T$$

ΔV = change in volume

V_0 = original area
ΔT = change in temperature
α = coefficient of linear expansion

Exercise

As a model of the ocean, think about water at 15 C (where its linear expansion coeff is $\alpha = 5 \times 10^{-5} \text{C}^{-1}$) in a fish tank of depth $D_0 = 4000$ m. If the temperature of the water rises by 1 C, how much does the depth change? (Assume the tank does *not* expand).

(A) 1 cm
(B) 20 cm
(C) 60 cm
(D) 1.5 m

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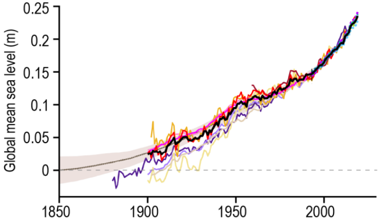
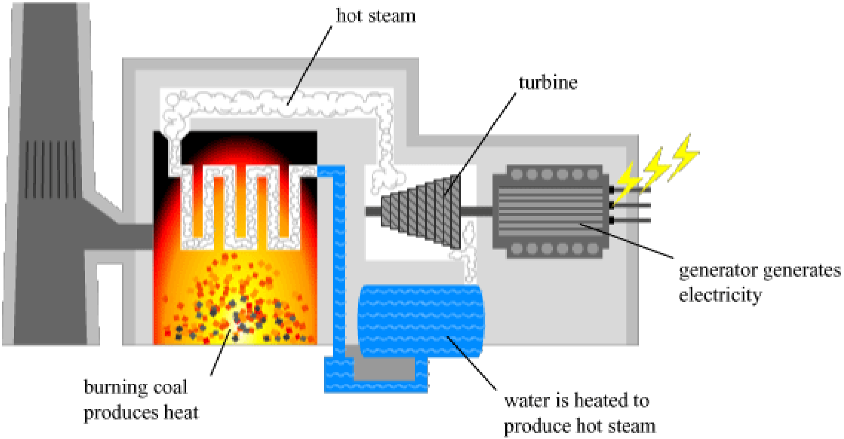
About half the observed rise is due to thermal expansion (of the top layers of the ocean).



Thermal Contraction: ice→water

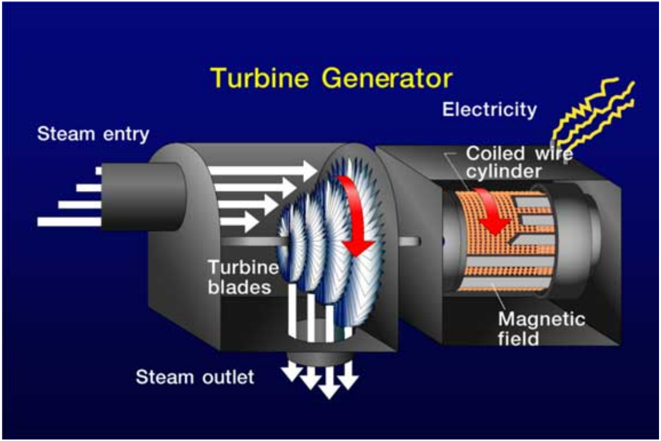
When ice melts to water, it *contracts*.
When water freezes to ice, it expands.

Heat engine: coal power plant



Turbine generator

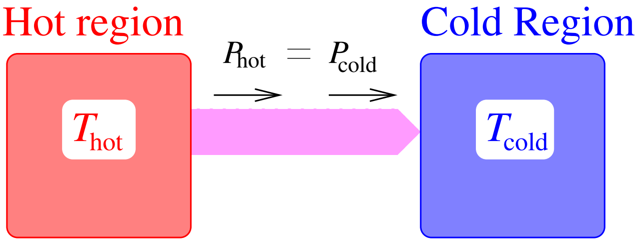
Using hot steam to generate electricity



Hot steam spins turbine which spins the generator, producing electricity.
This method is used in many types of electric power generator.

Heat flow with no heat engine or pump

Suppose you have a hot region next to a cold region.
Heat will flow from one to the other.



P_{hot} Joules/sec are leaving the hot region, and
P_{cold} Joules/sec are flowing into the cold region
So by conservation of energy

$$P_{\text{hot}} = P_{\text{cold}}$$

Heat flow with no heat engine or pump

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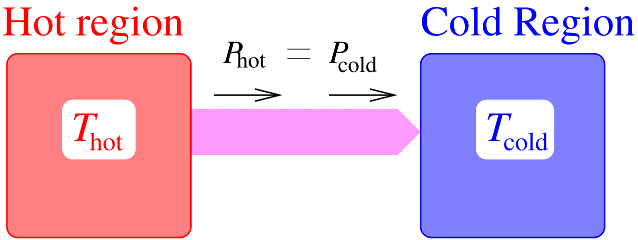


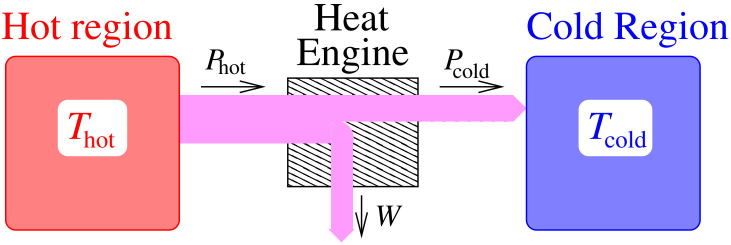
$P_{\rm hot}$ Joules/sec are leaving the hot region, and
$P_{\rm cold}$ Joules/sec are flowing into the cold region
So by conservation of energy

$$P_{\rm hot} = P_{\rm cold}$$

- A *heat engine* "siphons off" some of that heat flow as useful work.
- A *heat pump* does work and reverses the heat flow.

Heat engine

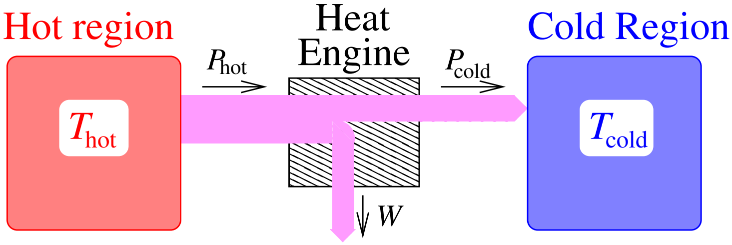
A heat engine "siphons off" some of the heat flow as useful work.



By conservation of energy, $$P_{\rm hot} = P_{\rm cold} + W$$

Heat engine

A heat engine "siphons off" some of the heat flow as useful work.



By conservation of energy, $P_{hot} = P_{cold} + W$

Efficiency = $\begin{array}{l}\text{fraction of the available heat} \\ \text{that is converted to work}\end{array} = \dfrac{W}{P_{hot}}$.

Efficiency is limited by the 2nd law of thermodynamics,

$$\frac{W}{P_{hot}} \leqslant \frac{T_{hot} - T_{cold}}{T_{hot}}$$

NB: Temperatures must be expressed in Kelvin!

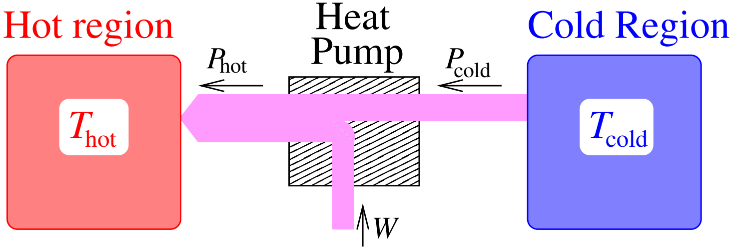
Exercise

How hot would you have to make the steam entering the turbine if you wanted the power plant to have a maximum efficiency of 90%?

(A) 3000 K
(B) 2100 K
(C) 1200 K
(D) 810 K

Heat Pump

A heat pump does work to make heat flow the “wrong way”, from cold to hot.



By conservation of energy, $P_{hot} = P_{cold} + W$

Coeff. of Performance, CoP $=$ amount of heat produced per amount of work done $= \frac{P_{hot}}{W}$.

Heat Pump

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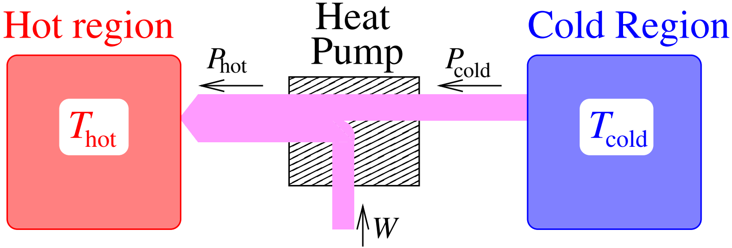


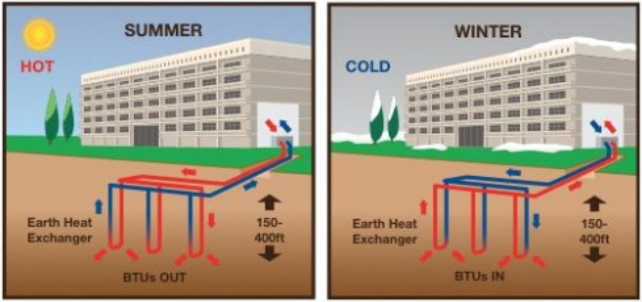
By conservation of energy, $P_{\text{hot}} = P_{\text{cold}} + W$

Coeff. of Performance, CoP $=$ amount of heat produced per amount of work done $= \dfrac{P_{\text{hot}}}{W}$.

CoP is limited by the 2nd law of thermodynamics,

$$\frac{P_{\text{hot}}}{W} \leqslant \frac{T_{\text{hot}}}{T_{\text{hot}} - T_{\text{cold}}}$$

Heat pumps for heating/cooling



Temperature underground is always about 13 C (55 F).

In summer, heat pump uses “coolness” of underground earth (relative to hot outside air) to cool the house

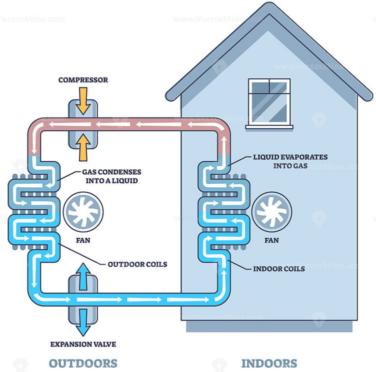
In winter, heat pump brings uses “warmness” of underground earth (relative to cold outside air) to warm the house

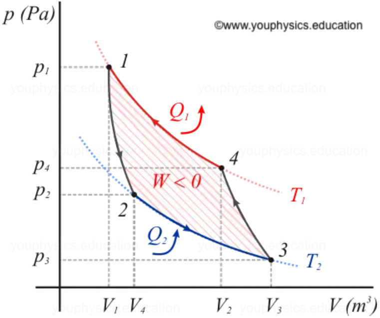
Exercise

If you heat your home in winter with a heat pump that pulls heat from the outside air (at about 0C) instead of the ground, what it the maximum efficiency?

(A) 1
(B) 8
(C) 15
(D) 42

How a heat pump works: Carnot cycle
(This will not be tested in exams/quizzes)





1 → 2 Allow refrigerant to expand quickly, it cools, doesn't absorb heat

2 → 3 Allow refrigerant to expand slowly, it stays the same temperature and absorbs heat

3 → 4 Compress refrigerant quickly, temperature rises but it doesn't emit heat

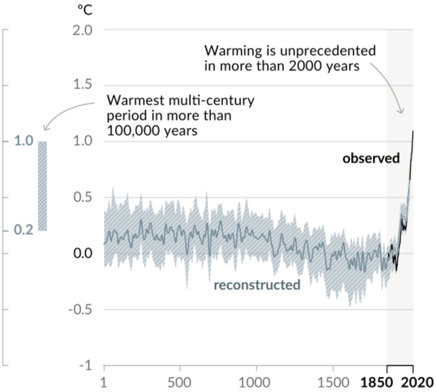
4 → 1 Compress refrigerant slowly, it stays the same temperature and loses heat to its surroundings

IPCC “Climate change 2021” conclusions

Intergovernmental Panel on Climate Change, 6th Assessment Report

- Human influence has warmed the climate at a rate that is unprecedented in at least the last 2000 years (about $+1\text{C} \approx +2^{\circ}\text{F}$ since the mid-20th century).
- Global surface temperature will continue to increase until at least the mid 21st century.
- By the end of the 21st century we will see global warming of at least $+2\text{C}$ unless deep reductions in CO_2 and other greenhouse gas emissions occur in the coming decades.

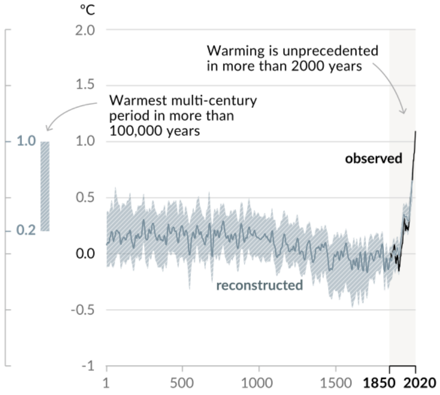
IPCC “Climate Change 2021” data

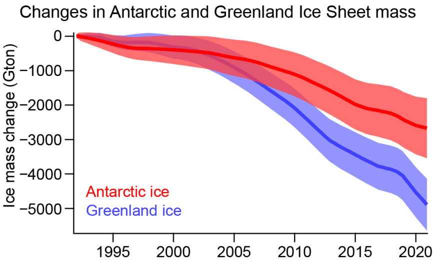


[IPCC 2021 report, Ch. 2]

[IPCC AR6 Summary for Policymakers]

IPCC "Climate Change 2021" data





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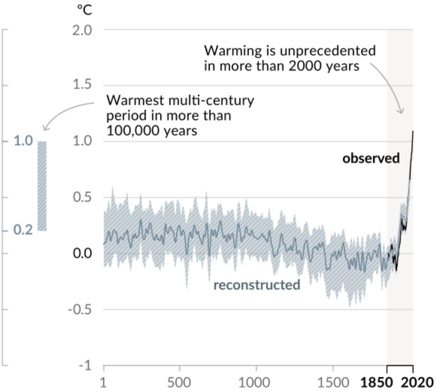

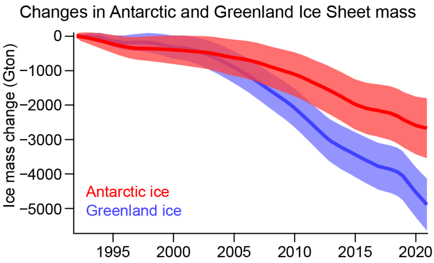

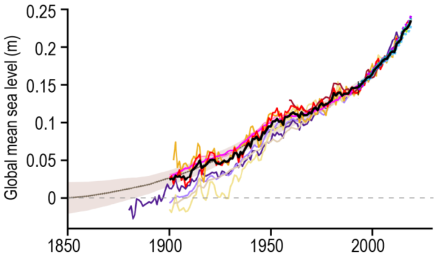

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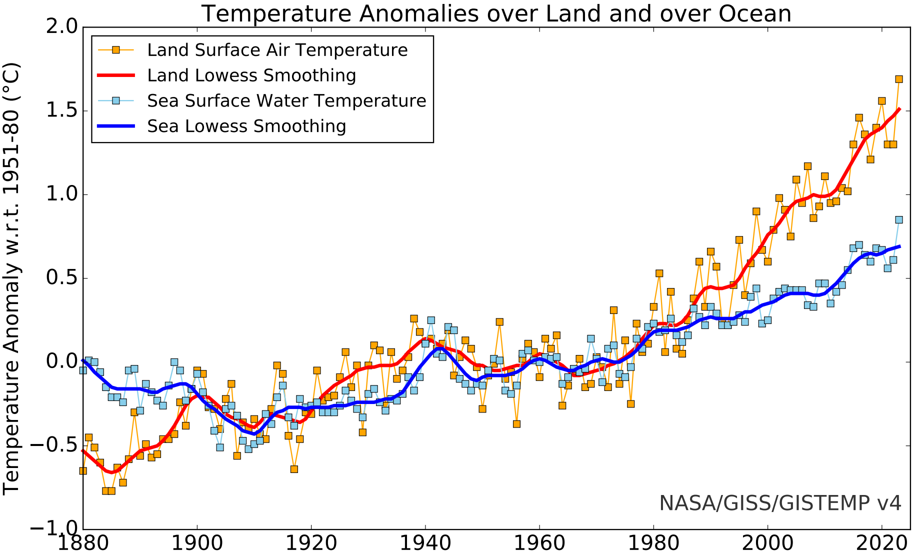
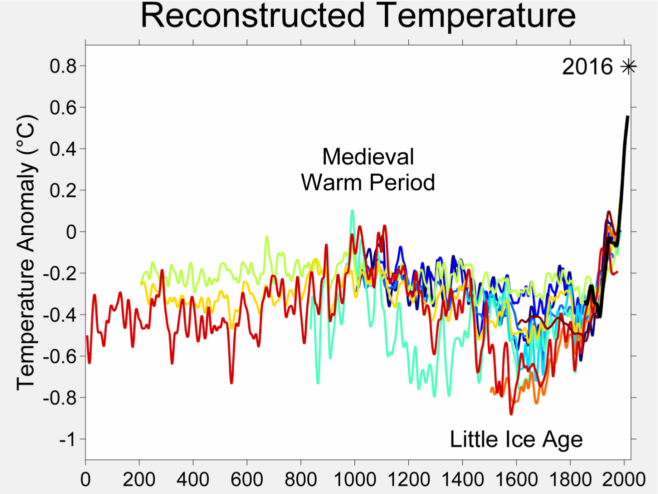
Global temperature: last 150 years



NASA Goddard dataset

Global temperature: last 2000 years

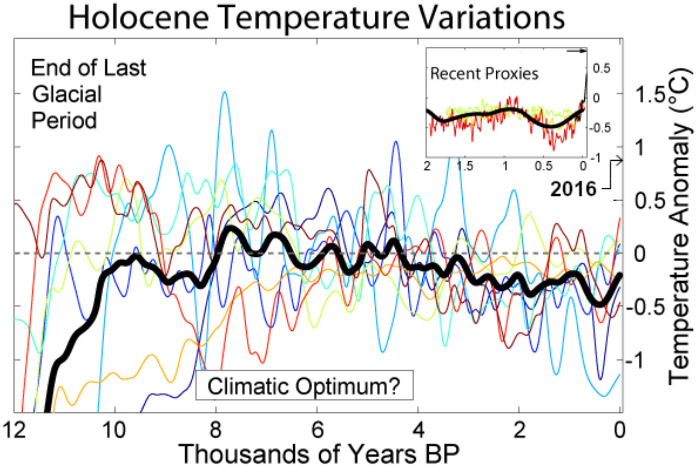


Data from:

- ice cores
- tree rings
- lake/ocean sediments
- coral Sr/Ca ratio
- boreholes

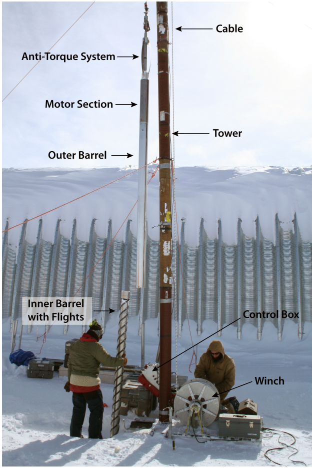
10 different published reconstructions of mean temperature over the last 2000 years, based on ice cores, tree rings, etc.
Instrumental history of temperature is also shown in black.

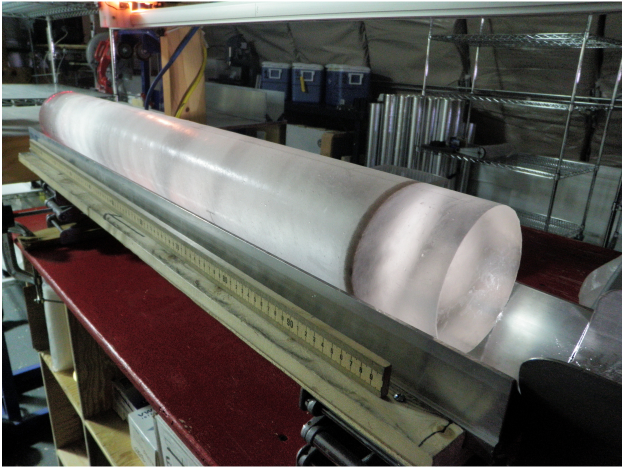
Global temperature: last 12,000 years



Data from ice cores, sediment cores, pollen.
Different colors are measurements at different locations.
Thick black line is the global average temperature.
Dashed line shows mid-20th-century average temperature.

Ancient climate: ice cores

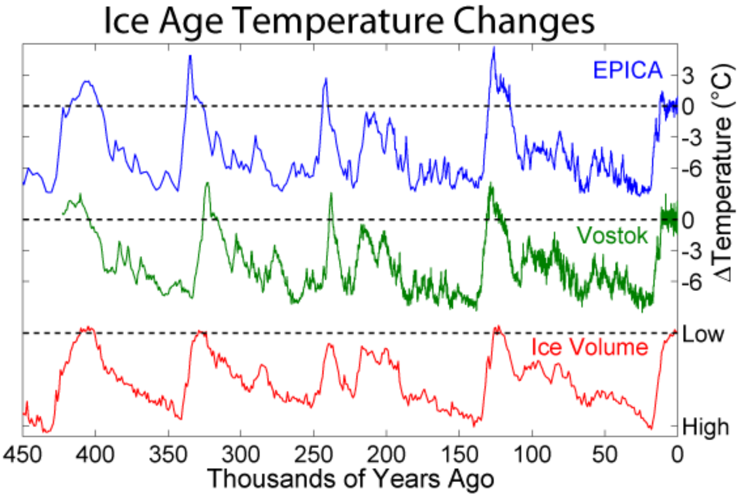




Dark band from volcanic eruption 21,000 years ago

Source: NSF Ice Core Facility

Global temperature: last $\frac{1}{2}$ million years



dashed lines: average values in mid 20th century

If temperatures rise by 3C, that will take us to the upper limits experienced in the last half million years.

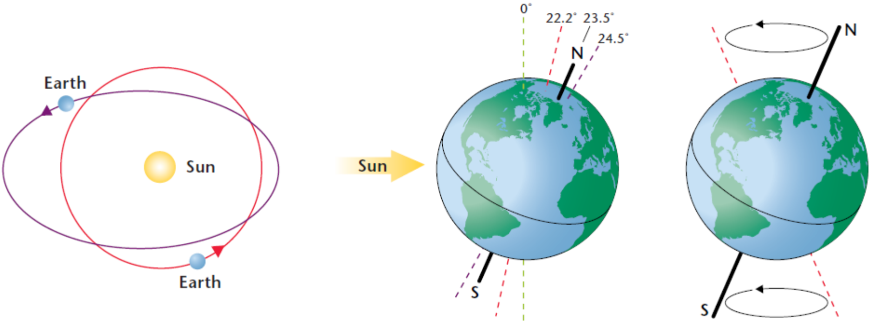
Exercise

During the last half million years,

(A) there has been only one ice age, and it lasted about 100,000 years
(B) there has been only one ice age which lasted about 10,000 years
(C) most of the time the earth has been in ice ages
(D) the earth has been in interglacials for about the same amount of time that it has been in ice ages

Ice age cycle: Milankovitch theory

Ice ages arise from slow changes in earth's orbit due to weak gravitational pull of other planets, especially Jupiter & Saturn.



Eccentricity Earth encounters more variation in the energy that it receives from the sun when Earth's orbit is elongated than it does when Earth's orbit is more circular.

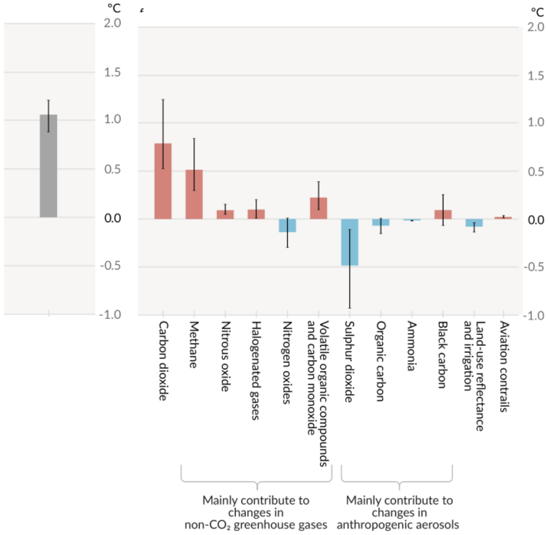
Tilt The tilt of Earth's axis varies between 22.2° and 24.5°. The greater the tilt angle is, the more solar energy the poles receive.

Precession A gradual change, or "wobble," in the orientation of Earth's axis affects the relationship between Earth's tilt and eccentricity.

Not shown: **Inclination**

What has caused the recent warming?

I.e. the +1 C rise in global avg temp since about 1950



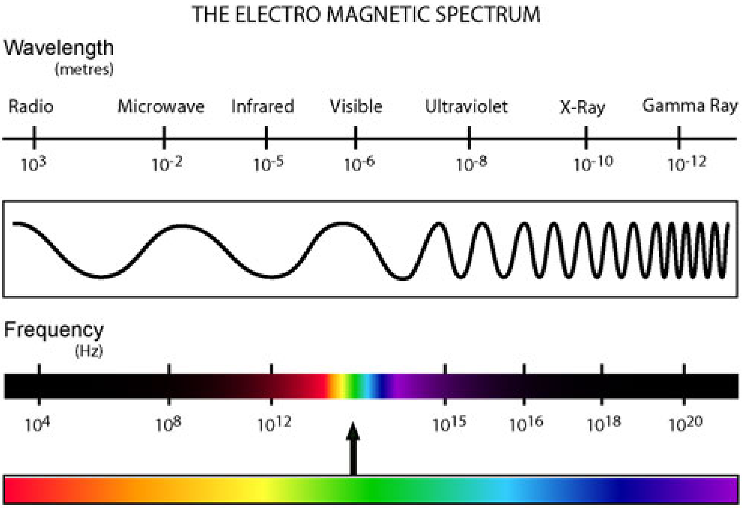
Mainly "Greenhouse Gases":

1) Carbon dioxide (CO_2)
2) Methane (CH_4)

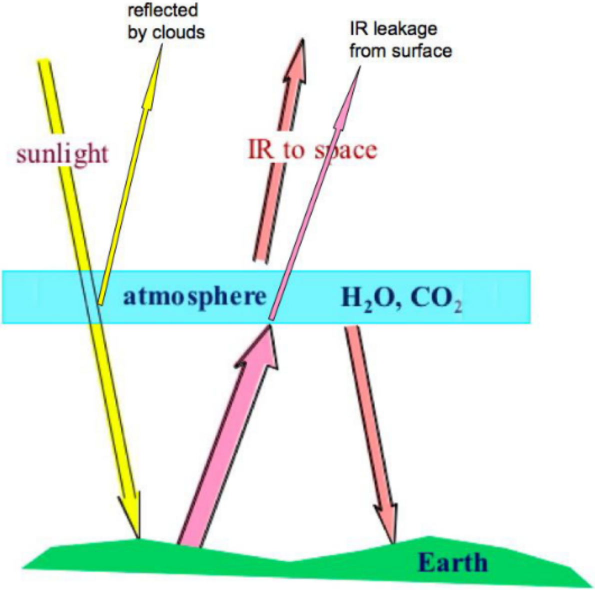
IPCC AR6 Summary for Policymakers

The spectrum of electromagnetic radiation

Like different "colors", but extending out beyond red and violet.



Greenhouse effect



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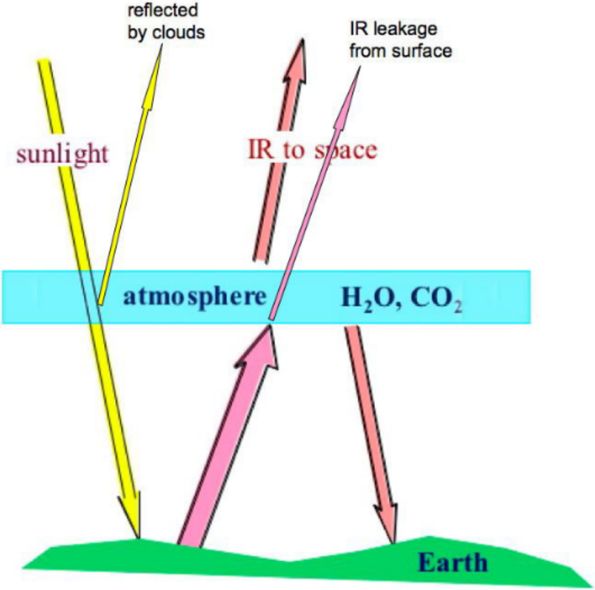


Heat in: sunlight
passes easily through atmosphere.

Heat out: infrared light partly absorbed and re-radiated by GHG in atmosphere.
Of that part, half goes out to space, half back to earth.

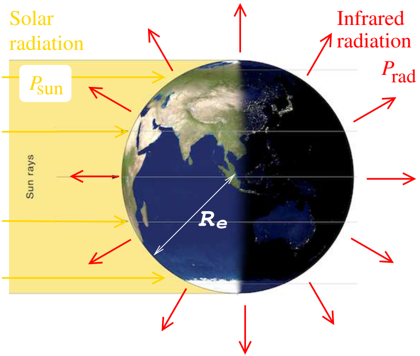
More GHG
$\Rightarrow$ less heat escapes
$\Rightarrow$ earth warms up.

Exercise

The term “greenhouse effect” refers to

(A) reduction in solar heating by reflection of sunlight by clouds or the polar ice caps
(B) reduction in earth’s infrared emission by atmospheric gases that are not transparent to infrared light
(C) increase in earth’s infrared emission in the form of direct emission of infrared light from the earth’s surface
(D) scattering of sunlight by particles in the atmosphere

Simple model of global climate

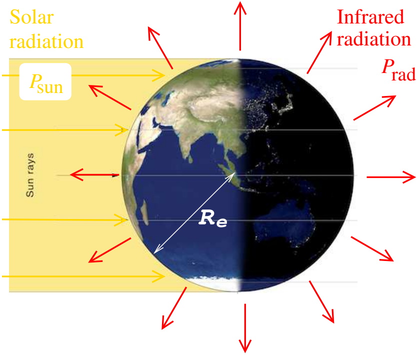


Exercise

What is the power (energy per second) delivered to the earth via sunlight?
Earth's radius is $R_e = 6400\,\text{km}$

(A) $1.8 \times 10^{17}\,\text{W}$ (B) $3.6 \times 10^{17}\,\text{W}$
(C) $7.0 \times 10^{17}\,\text{W}$ (D) $1.4 \times 10^{18}\,W$

Simple model of global climate



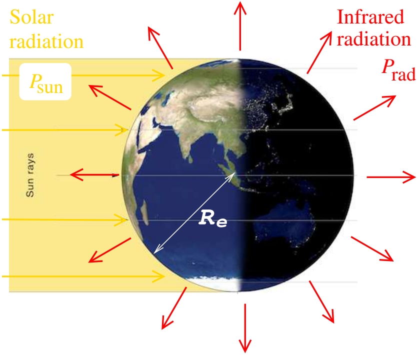
Power arriving from sun

$$P_{sun} = F \times \underbrace{\pi R_e^2}_{\text{target area}} \times \overbrace{\alpha}^{\text{absorption fraction}}$$

F = power in sunlight $= 1365\,\mathrm{W m^{-2}}$

α = fraction absorbed by Earth $= 0.7$

Simple model of global climate



Power arriving from sun

$$P_{\text{sun}} = F \times \underbrace{\pi R_e^2}_{\text{target area}} \times \overbrace{\alpha}^{\text{absorption fraction}}$$

F = power in sunlight = $1365\,\mathrm{W m^{-2}}$

α = fraction absorbed by Earth = 0.7

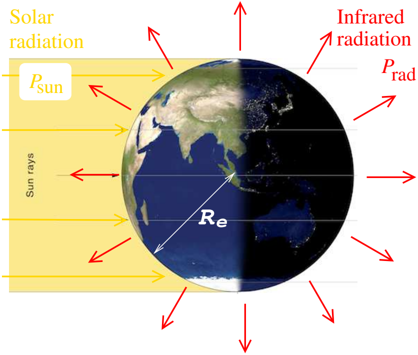
Power radiated away

$$P_{\text{rad}} = \sigma \times \underbrace{4\pi R_e^2}_{\text{surface area}} \times T_{\text{earth}}^4 \times \overbrace{\varepsilon}^{\text{emissivity}}$$

$\sigma = 5.67 \times 10^{-8}\,\mathrm{W m^{-2} K^{-4}}$

ε = Earth's infrared emissivity = 0.62

Simple model of global climate



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α = fraction absorbed by Earth = 0.7

Power radiated away

$$P_{rad} = \sigma \times \underbrace{4\pi R_e^2}_{\text{surface area}} \times T_{earth}^4 \times \overbrace{\varepsilon}^{\text{emissivity}}$$

$\sigma = 5.67 \times 10^{-8}\,\mathrm{Wm^{-2}K^{-4}}$

ε = Earth's infrared emissivity = 0.62

In equilibrium, earth radiates energy away at the same rate as it arrives,

$$P_{sun} = P_{rad} \quad \Rightarrow \quad T_{earth}^4 = \frac{F\alpha}{4\sigma\varepsilon}$$

Exercise

Estimate the equilibrium temperature of earth's surface, where cooling via infrared radiation balances the heat arriving in sunlight.

(A) 407 K (B) 293 K (C) 287 K (D) 273 K

Exercise

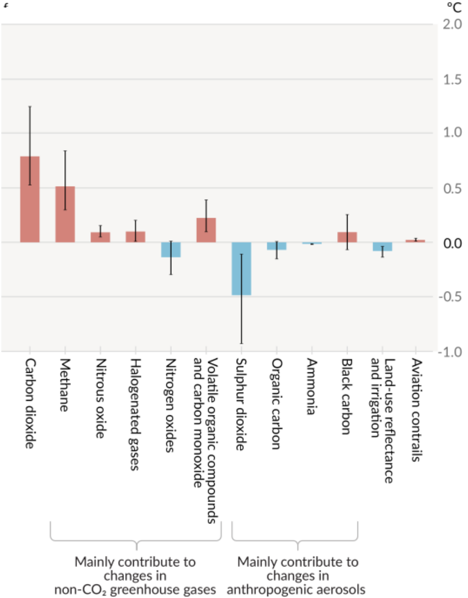
Estimate the equilibrium temperature of earth's surface, where cooling via infrared radiation balances the heat arriving in sunlight.

(A) 407 K (B) 293 K (C) 287 K (D) 273 K

Suppose greenhouse gas levels increase, so earth's emissivity drops from 0.62 to to 0.60. What is the resultant change in earth's surface temperature?

(A) +10 C (B) +1 C (C) +5 C (D) +2 C

How human activities cause warming



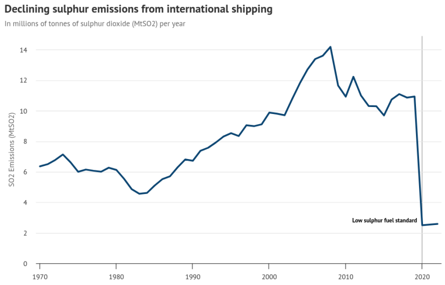
1) Carbon dioxide: greenhouse gas
2) Methane (CH_4): greenhouse gas
3) Nitrous Oxide (N_2O): greenhouse gas
4) Halogenated gases (e.g. refrigerants): greenhouse gases
5) Nitrogen Oxides (NO_x): anti-greenhouse-gas; breaks down to hydroxyl (OH) radicals
6) Carbon monoxide (CO) and volatile organics: protects greenhouse gases by destroying hydroxyl radicals
7) Sulphur dioxide (SO_2): sunlight reflector via creation of sulphate particles
8) Organic carbon: sunlight reflector, carbon compounds that create white clouds
9) Black carbon: sunlight absorber

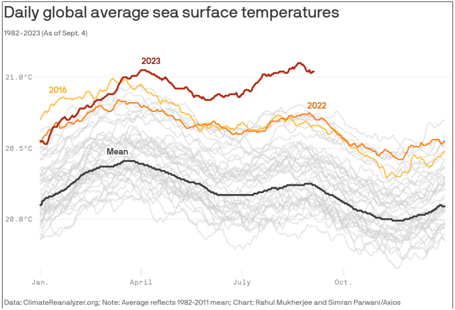
Clouds from maritime SO_2 emissions

Cargo ships burning high-sulfur fuel create clouds ("ship tracks") over the ocean.

But in 2020 the International Maritime Organization lowered the maximum percentage of sulfur from 3.5% to 0.5% for all ships operating worldwide.

SO_2 as an anti-greenhouse gas

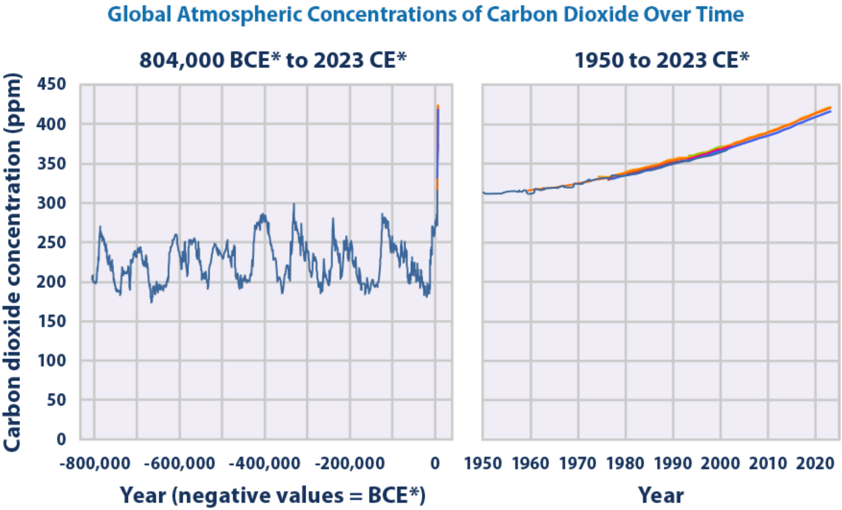




When sulfur content of ship fuel dropped, cloud formation dropped, and global average sea temperature rose.

Carbonbrief article

History of carbon dioxide levels



EPA Climate Change Indicators

Oct 2023: CO_2 is 419 parts per million

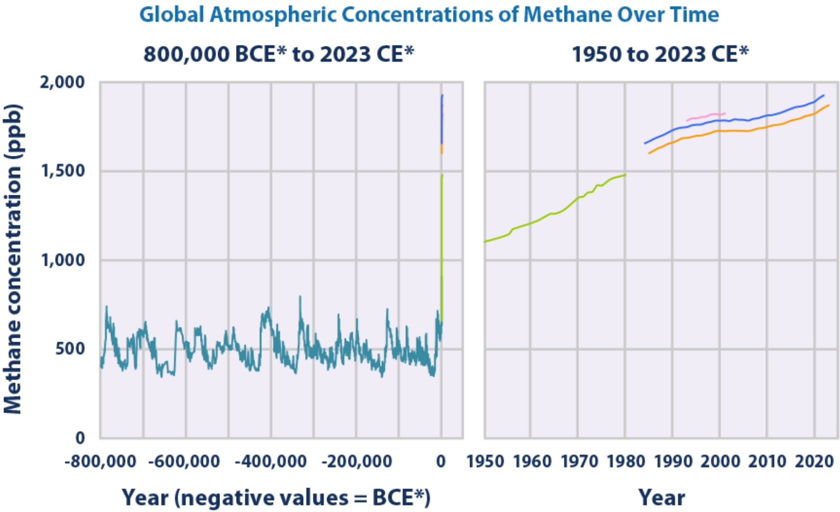
Oct 2024: CO_2 is 422 parts per million https://www.co2levels.org/

Exercise

If we wanted to return the CO_2 level to its 1990 level, roughly how many tons of CO_2 would we have to remove from the atmosphere? (Mass of atmosphere is 5×10^{15} tons.)

(A) 300 billion tons
(B) 1 billion tons
(C) 13 billion tons
(D) 1 trillion tons

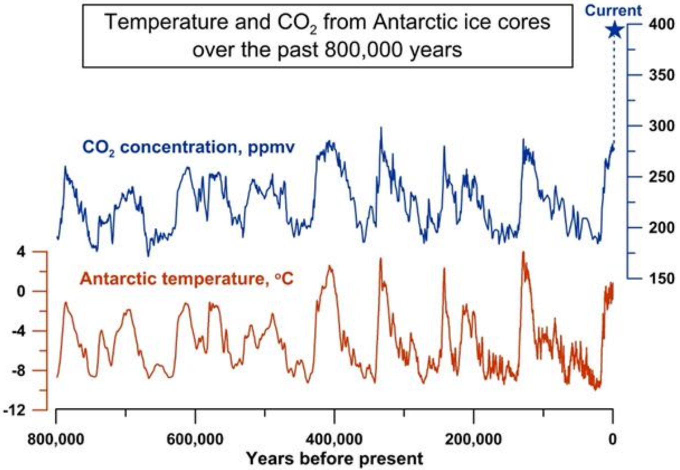
History of methane levels



[EPA Climate Change Indicators]

CO_2 and CH_4 now substantially exceed the highest concentrations recorded in ice cores during the past 800,000 years.

CO_2 and temperature, correlation



New Zealand National Institute of Water and Atmospheric Research

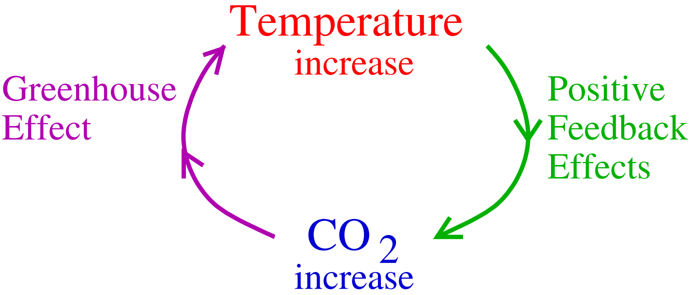
CO_2 and temperature, causation

In the detailed record, we sometimes see

$CO_2\uparrow$ followed by temperature$\uparrow$

but we also see

temperature$\uparrow$ followed by $CO_2\uparrow$



Currently, we are seeing extraordinarily fast $CO_2\uparrow$, so we expect (and see) a resultant warming.

Exercise

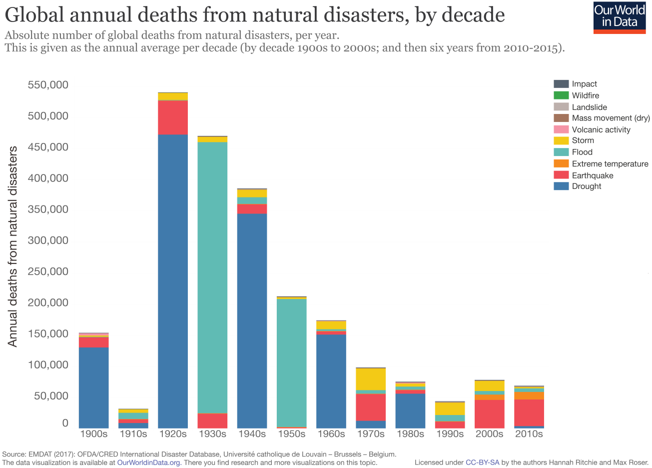
Which of the following has occurred over the last 25 years?

(A) global average temperature has increased by more than 1C
(B) atmospheric methane level has doubled
(C) atmospheric CO_2 level has increased by about 40%
(D) average sea level has risen by about 10 cm

“Extreme Weather” on the increase?

- Deaths due to natural disasters: Decreasing
- Hurricanes Possibly getting stronger
- Tornadoes No strong trend
- Heat waves Some upward trend
- Droughts No clear trend
- Heavy rain Slight upward trend

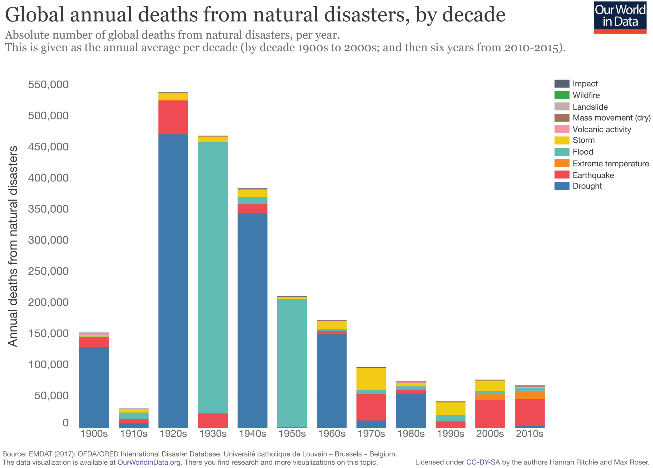
Death rate from natural disasters



`https://ourworldindata.org/natural-disasters`

Dramatic *decrease* over 20th century. Why?

Death rate from natural disasters

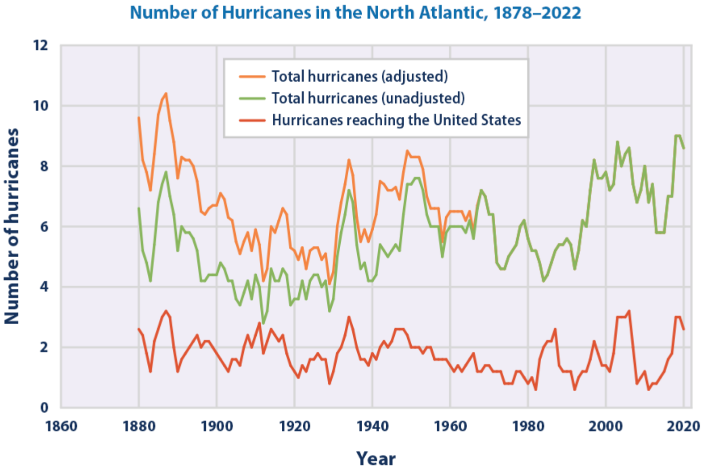


`https://ourworldindata.org/natural-disasters`

Dramatic *decrease* over 20th century. Why?

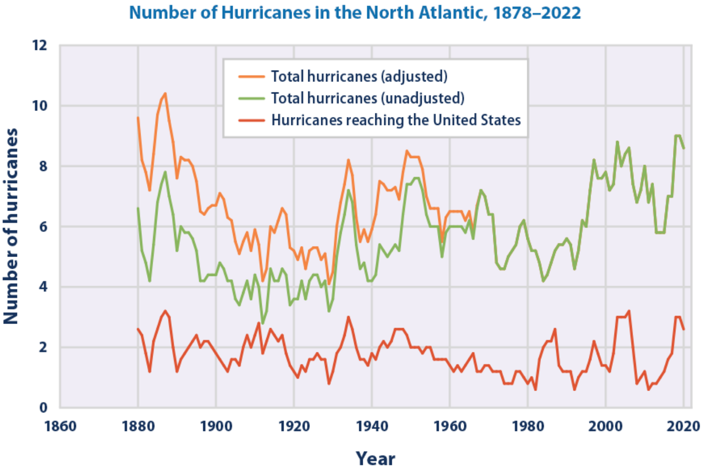
Increase in standard of living: better housing, transportation, medical infrastructure, etc, partly due to fossil fuels.

Hurricanes



EPA, Climate Change Indicators

Hurricanes

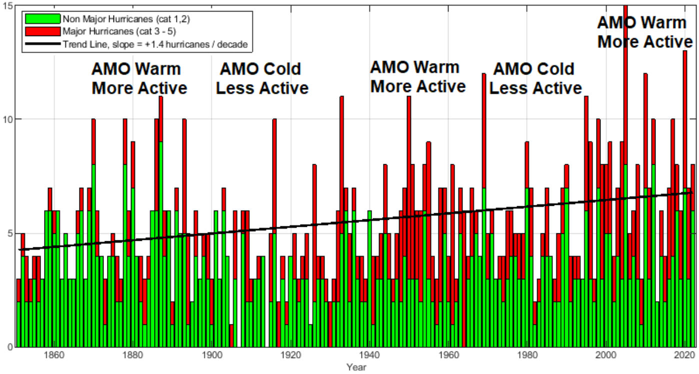


EPA, Climate Change Indicators

No upward trend, especially in hurricanes reaching the U.S., which are most reliably reported over time.

Severe Hurricanes

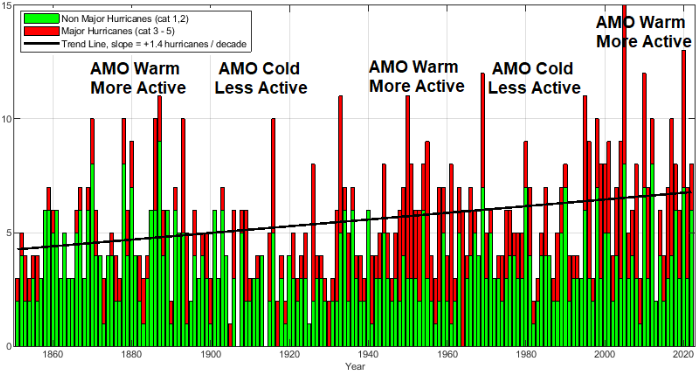
(AMO = Atlantic Multi-decadal Oscillation)



Dale Ward, U of Arizona

Severe Hurricanes

(AMO = Atlantic Multi-decadal Oscillation)

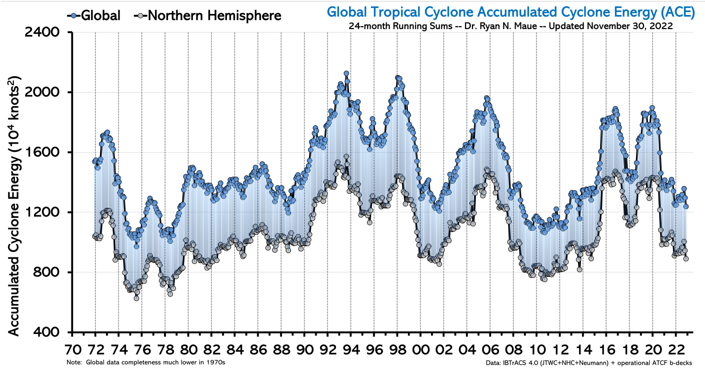


Dale Ward, U of Arizona

Gradual upward trend in Cat 3,4,5 hurricanes (+0.14/yr per decade), but the AMO is also a big influence.

Global Hurricane/Cyclone Energy Index

Global ACE measures the total wind energy realized over the entire life cycle of all storms



Dale Ward, U of Arizona

Global Hurricane/Cyclone Energy Index

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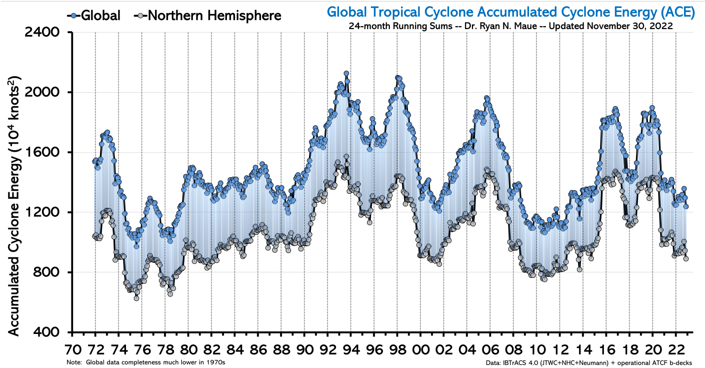
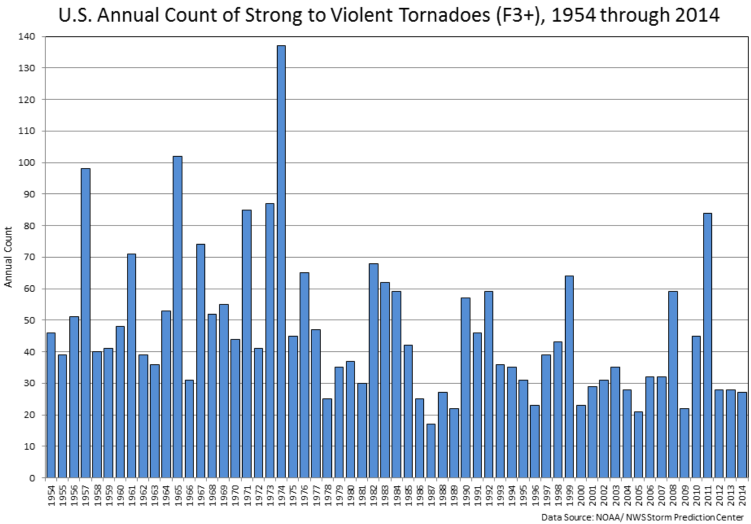


Dale Ward, U of Arizona

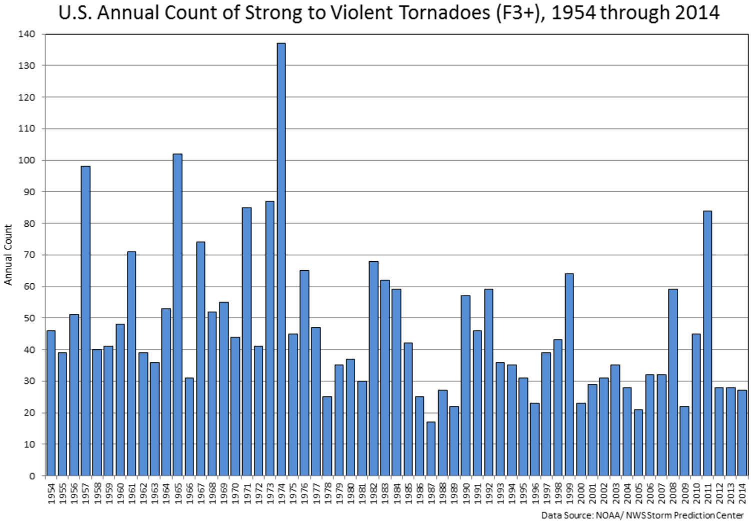
Not much upward trend.

Strong tornadoes in U.S.



U.S. National Oceanic and Atmospheric Administration

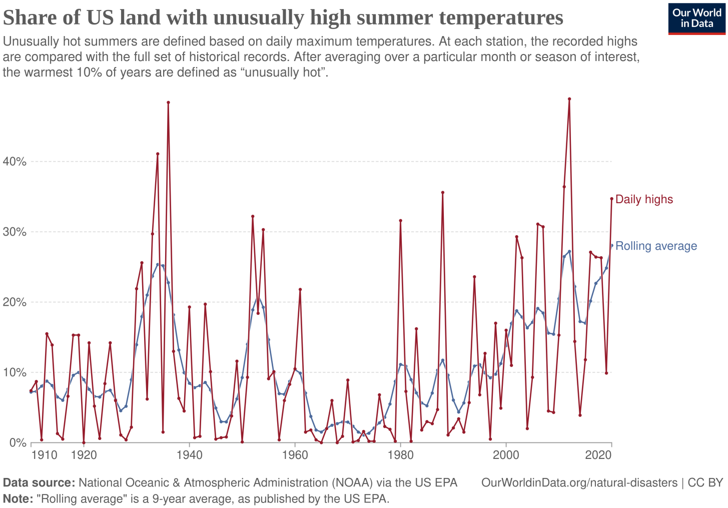
Strong tornadoes in U.S.



U.S. National Oceanic and Atmospheric Administration

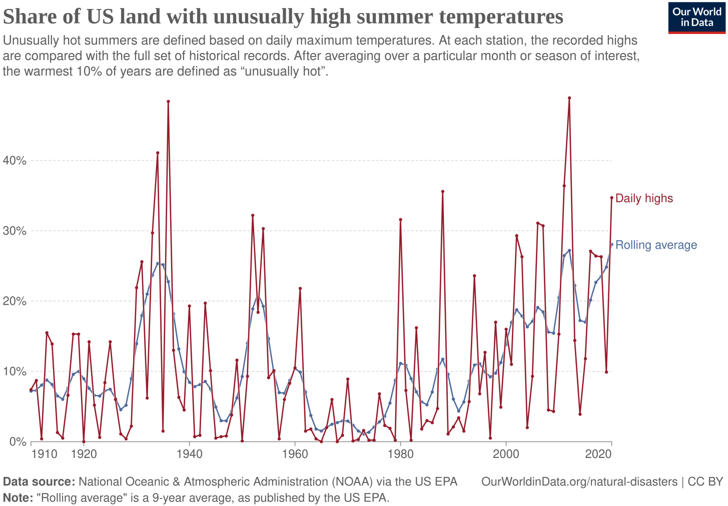
No increasing trend.

Heatwaves in U.S., last 100 years



https://ourworldindata.org/us-weather-climate

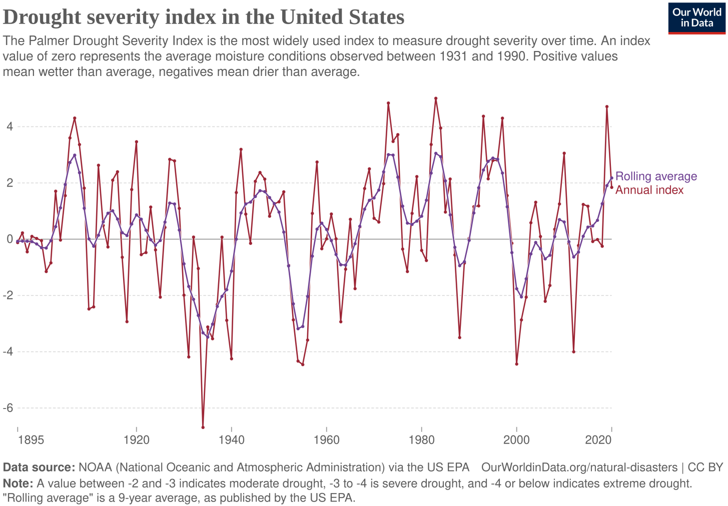
Heatwaves in U.S., last 100 years



https://ourworldindata.org/us-weather-climate

Increasing trend since 1970s, but note peak in 1930s.

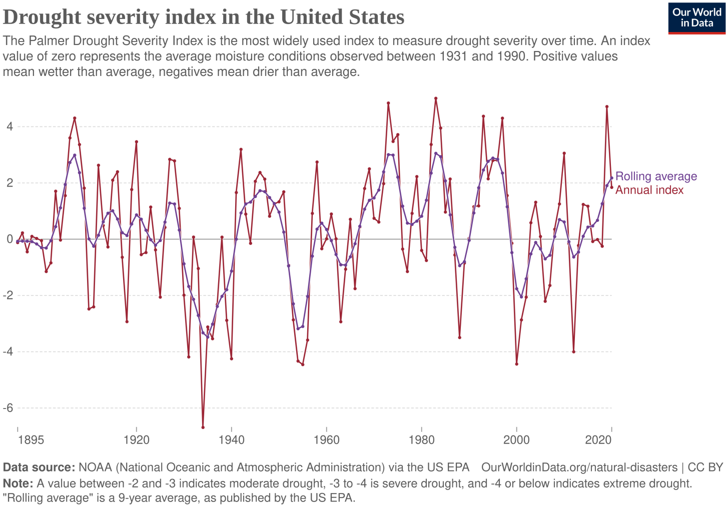
Droughts in U.S., last 120 years



https://ourworldindata.org/us-weather-climate

Negative = drought,

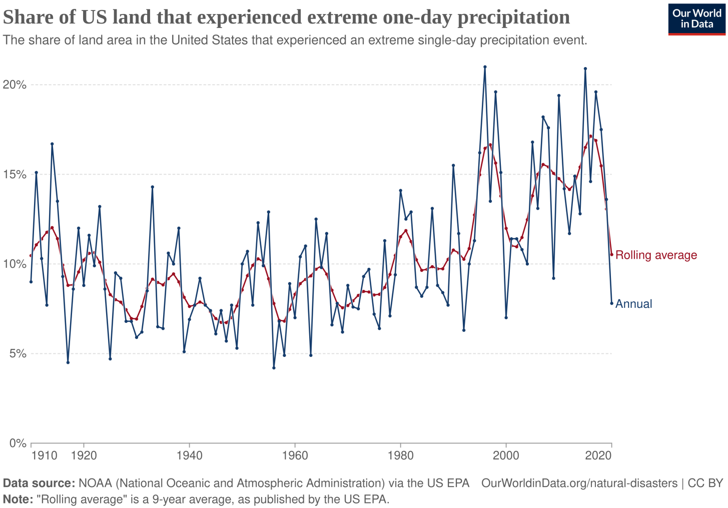
Droughts in U.S., last 120 years



https://ourworldindata.org/us-weather-climate

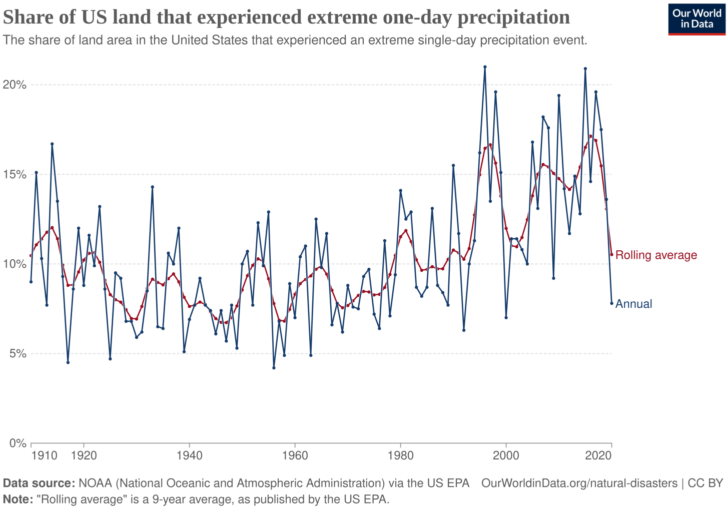
Negative = drought, e.g. 1930s “dustbowl”. No increasing trend.

Heavy rainfall in U.S., last 100 years



https://ourworldindata.org/us-weather-climate

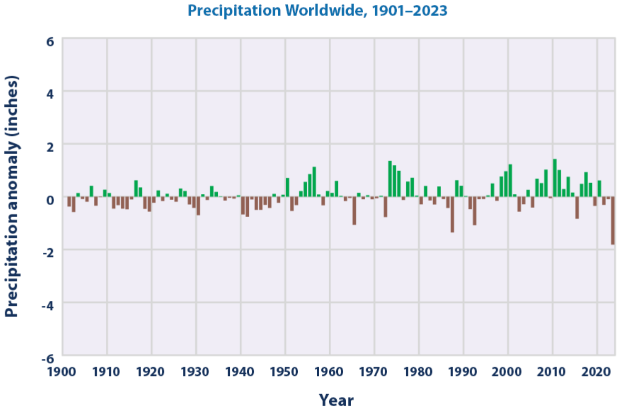
Heavy rainfall in U.S., last 100 years



https://ourworldindata.org/us-weather-climate

Slight upward trend since 1950s

Worldwide precipitation



Data source: NOAA (National Oceanic and Atmospheric Administration). (2024). Extended version of GPCC dataset originally published in Blunden, J., Boyer, T., & Bartow-Gillies, E. (2023). State of the climate in 2022. *Bulletin of the American Meteorological Society, 104*(9), S1–S516. https://doi.org/10.1175/2023BAMSStateoftheClimate.1

For more information, visit U.S. EPA's "Climate Change Indicators in the United States" at www.epa.gov/climate-indicators.

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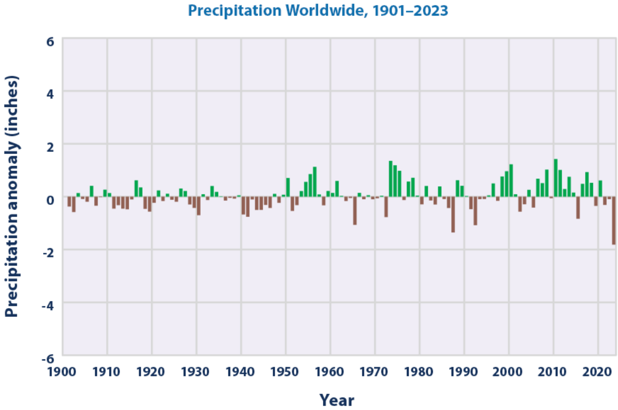
Worldwide precipitation



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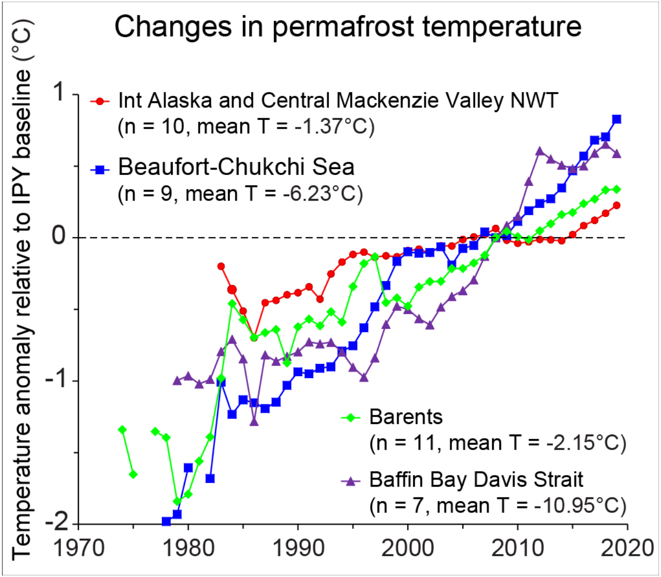
https://www.epa.gov/climate-indicators

Some upward trend, but lots of fluctuation.

Permafrost

The grey area under the soil is permafrost: ice, soil, and organic matter. When it melts it releases greenhouses gases CH_4 and CO_2 from decay of organic matter.

Permafrost temperature



IPCC 2021 Ch 2; IPY = International Polar Year (2007-8)

Melting permafrost: subsidence

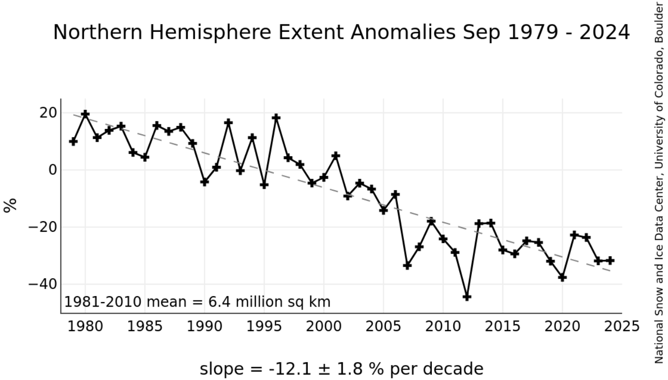
Alaskan house with severe damage from melting permafrost under foundation.
Other consequences: coastal erosion, damage to roads and other infrastructure.

Melting permafrost: erosion

Coastal erosion due to melting permafrost in Shishmaref, Alaska.

Source: [New York Times article, 2016]

Arctic sea ice cover

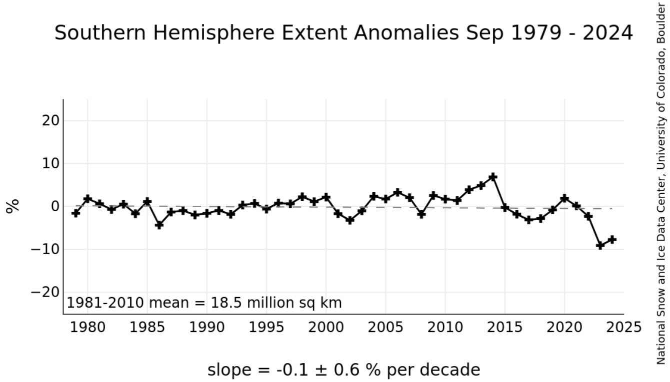


"Anomalies" means value relative to 1979-2000 mean
[National Snow and Ice Data Center]

Significant ongoing loss of north polar ice.

Antarctic sea ice cover

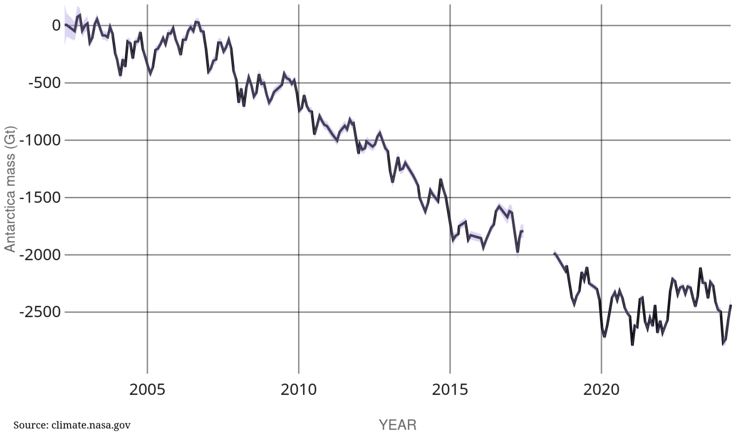
Remember, Antarctic is a land continent. This is just the ice on the sea around it.



"Anomalies" means value relative to 1979-2000 mean
National Snow and Ice Data Center

Sea ice area is not changing much, but total Antarctic ice mass is dropping (see next slide).

Antarctic ice mass loss



GRACE satellite data, NASA

Clear loss of Antarctic ice over time.

GRACE consists of 2 satellites that probe earth's gravitational field, measuring small variations in earth's surface density.

Greenland ice mass loss

GRACE satellite data, NASA

Clear loss of Greenland ice over time.

Exercise

Which of the following has occurred over the last 25-30 years?

(A) strong tornadoes have become more frequent in the U.S.
(B) droughts have become more frequent in the U.S.
(C) temperature of permafrost in Alaska has risen by about 0.5C
(D) Greenland has lost a total of about a billion tons of ice

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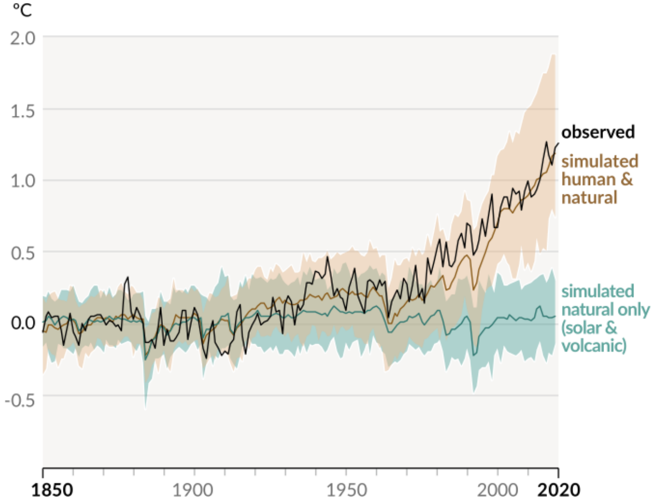
(C) temperature of permafrost in Alaska has risen by about 0.5C
(D) Greenland has lost a total of about a billion tons of ice

Suppose all the ice lost from Greenland in the last 20 years has gone in to the global ocean, whose area is 360 million km^2. How much has sea level risen as a result?

(A) 1 cm (B) 1 mm (C) 0.1 mm (D) 0.01 mm

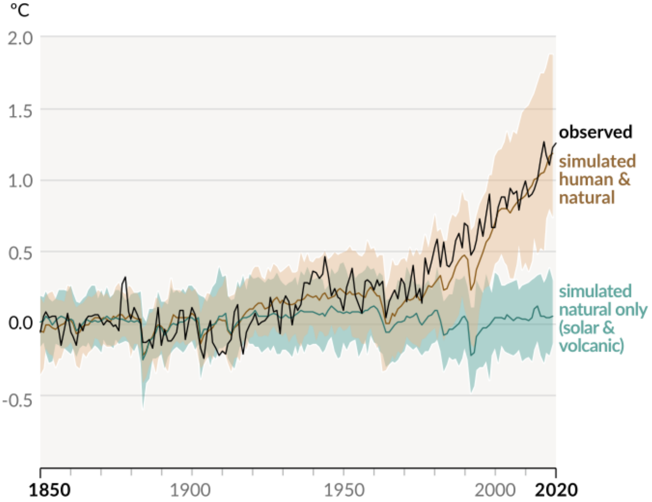
Global warming: anthropogenic?



What are the sudden dips in 1883, 1963, 1991?

IPCC AR6 Summary for Policymakers

Global warming: anthropogenic?



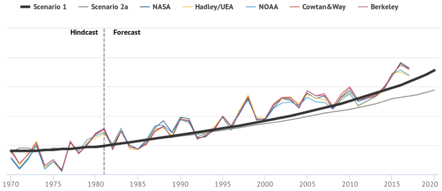
What are the sudden dips in 1883, 1963, 1991?

Krakatoa (1883)
Agung? (1963)
Pinatubo (1991)

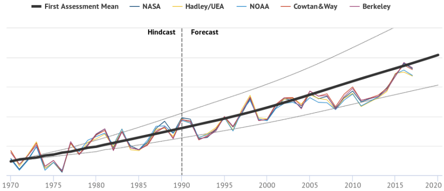
IPCC AR6 Summary for Policymakers

Global warming since about 1960 seems to be anthropogenic

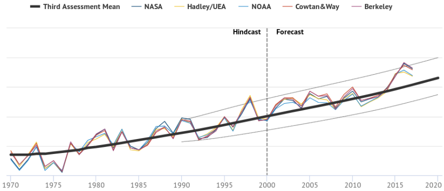
Reliability of climate models



Hansen 1981



IPCC 1990



IPCC 2001

Source: Carbonbrief Article

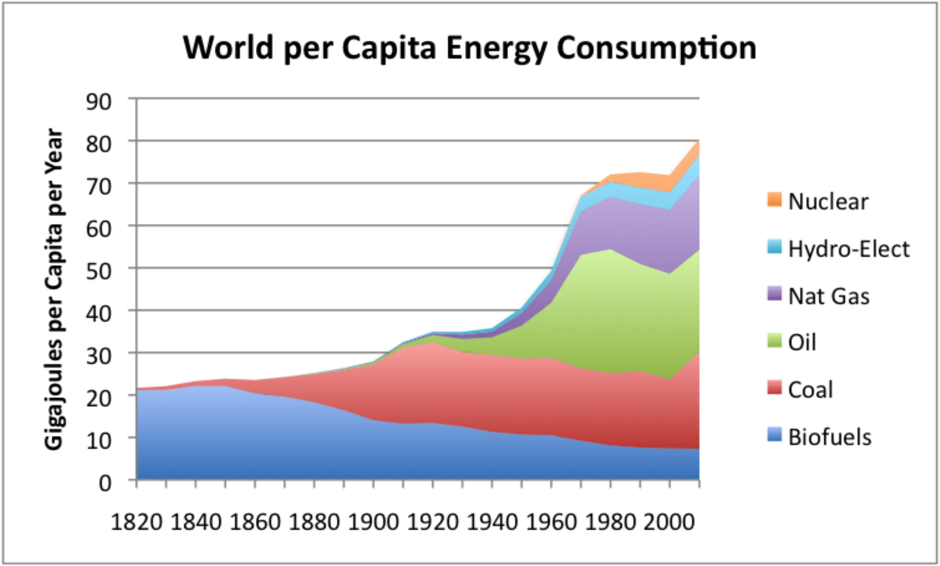
Negative effects of climate change

- changes in food production regions ⇒ famine, mass migration
- changes in availability of water ⇒ drought, mass migration
- flooding of coastal communities ⇒ mass migration
- expansion of tropical disease regions, e.g. via mosquitos ⇒ health costs
- Positive feedback leading to further warming, e.g.
  - methane from melting permafrost
  - less reflection of sunlight when ice caps melt

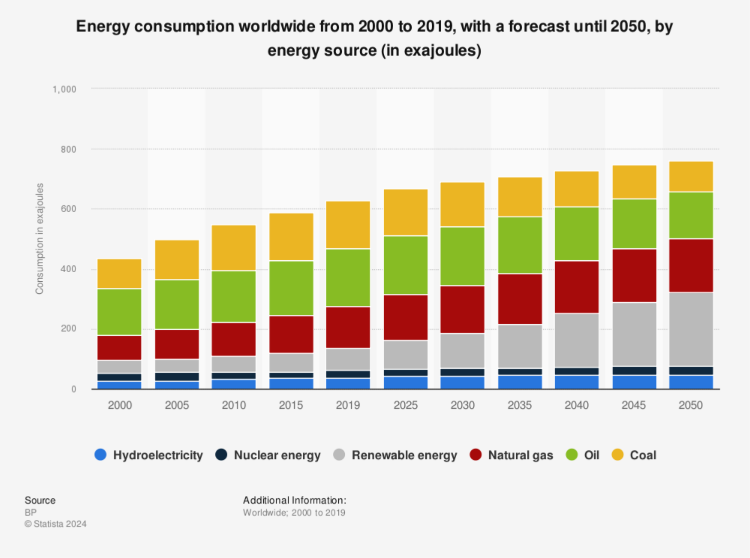
Summary (for humans): disruption of current patterns of settlement and sustenance

People with the lowest wealth and standard of living will be affected most severely by mass migration, food production shifts, droughts, etc.

History of world energy generation

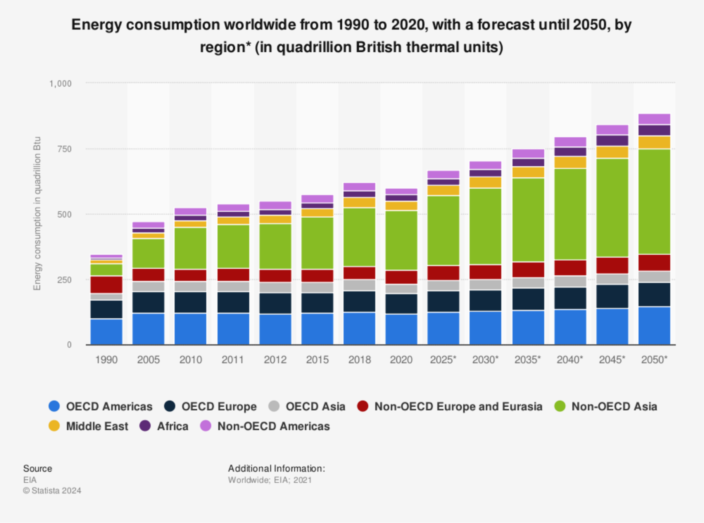


Projected world energy consumption 1



Source: Statistica

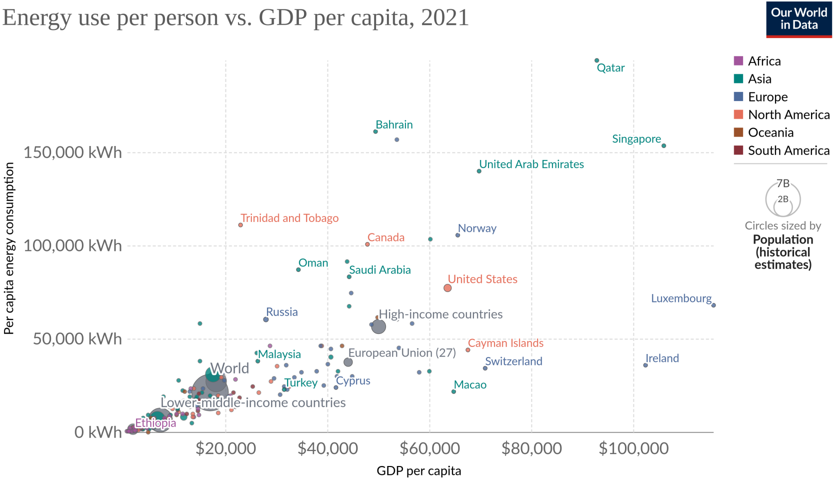
Projected world energy consumption 2



Source: [Statistica]

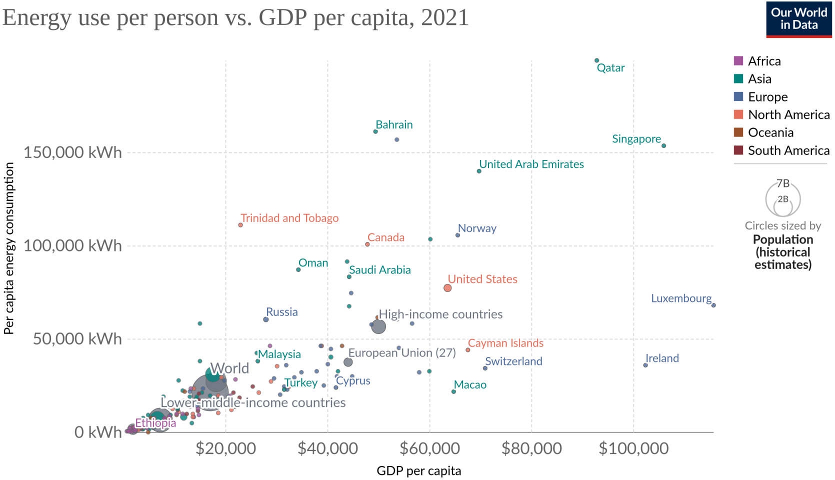
Most expected growth is in Asia

Energy usage vs income



[Source](#)

Energy usage vs income



[Source](#)

y-axis: **energy used** per person per year, in kWh

x-axis: **Gross Domestic Product** per person per year, in $

50,000 kWh/person/year for every $40,000/person/year, i.e. ~ 1 kWh/$

Exercise

Between 2002 and 2010, the average annual income of people in Kenya doubled. One would expect that during this time the annual energy consumption per person in Kenya roughly

(A) went down by 50%
(B) changed by less than 10%
(C) quadrupled
(D) doubled

Energy Needs vs. Global Warming

Energy Needs vs. Global Warming

1. Use fossil fuels: coal, oil, natural gas
   Adds CO_2 to the atmosphere
2. Geoengineering:
   Compensate for human activity by altering other factors
   (usually: increase IR emissivity or decrease absorption fraction)
   Economically or politically feasible?
3. Reduce future GHG emissions
   - Efficiency: use less energy
   - Low-carbon electricity generation
   - Biofuels (liquid fuels made from recently-living plants)

   very little achieved on this so far
   there will be continued global warming
4. Improve human adaptation and flexibility
   e.g.: people with more wealth are more resilient

Fossil fuels

- Which fossil fuel is "best"? (Or least worst)
- Will we run out of fossil fuels?
- Are fossil fuels getting more expensive?
- Increasing fossil fuel supply: directional drilling, fracking

Which fossil fuel is “best”?

Coal:

Which fossil fuel is “best”?

Coal: $C + O_2 \rightarrow CO_2$

Oil:

Which fossil fuel is "best"?

Coal: $C + O_2 \rightarrow CO_2$

Oil: $CH_2 + O + O_2 \rightarrow CO_2 + H_2O$

Natural Gas:

Which fossil fuel is "best"?

Coal: $C + O_2 \rightarrow CO_2$

Oil: $CH_2 + O + O_2 \rightarrow CO_2 + H_2O$

Natural Gas: $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$

Coal: *all* the energy comes from burning carbon to CO_2

Oil: *most* of the energy comes from burning carbon

Natural gas: methane is "mostly hydrogen": only about *half* of the energy comes from burning carbon.

Problem: leakage of methane (80 times more greenhouse effect than CO_2) during drilling (NY Times article, Sept 2020)

Exercise

How much CO_2 is produced by burning 1 kg of coal?

(A) 18 kg (B) 4 kg (C) 9 kg (D) 1 kg

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How much heat energy is produced by burning 1 kg of coal?

(A) 8 kWh (B) 25 kWh (C) 2.5 kWh (D) 0.8 kWh

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How much heat energy is produced by burning 1 kg of coal?
(A) 8 kWh (B) 25 kWh (C) 2.5 kWh (D) 0.8 kWh

When burning coal, how much CO_2 is produced per kWh of heat energy?
(A) 1.5 kg/kWh (B) 3 kg/kWh (C) 0.5 kg/kWh (D) 0.3 kg/kWh

Exercise

How much CO_2 is produced by burning 1 kg of coal?
(A) 18 kg (B) 4 kg (C) 9 kg (D) 1 kg

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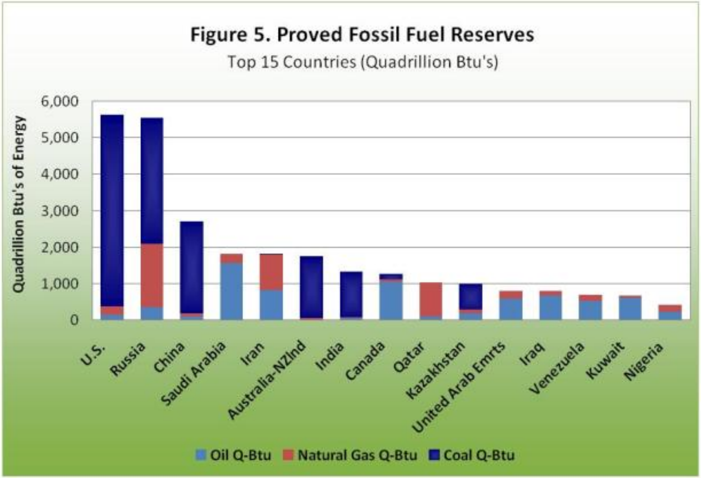
When burning coal, how much CO_2 is produced per kWh of heat energy?
(A) 1.5 kg/kWh (B) 3 kg/kWh (C) 0.5 kg/kWh (D) 0.3 kg/kWh

When burning natural gas, how much CO_2 is produced per kWh of heat energy?
(A) 1.5 kg/kWh (B) 3 kg/kWh (C) 0.5 kg/kWh (D) 0.2 kg/kWh

Is there enough coal, gas, and oil?



[Agricultural Marketing Resource Center]

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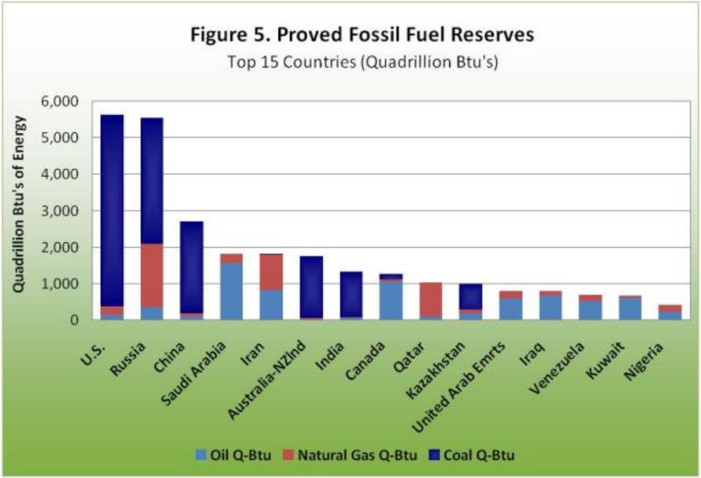
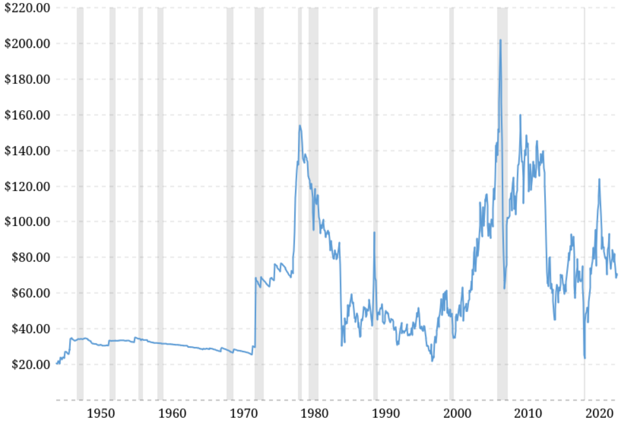


Agricultural Marketing Resource Center

U.S. usage: 70 quad/year of oil and natural gas, 8 quad/year of coal. So there is enough for many years to come.

Is oil getting more expensive?

Is oil becoming more expensive? Inflation-adjusted data:



[Macrotrends]

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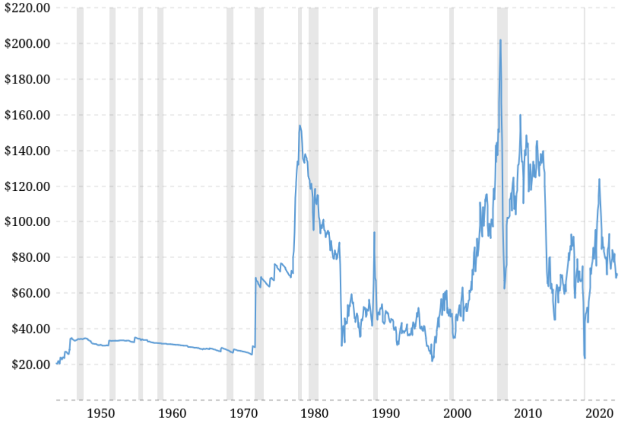
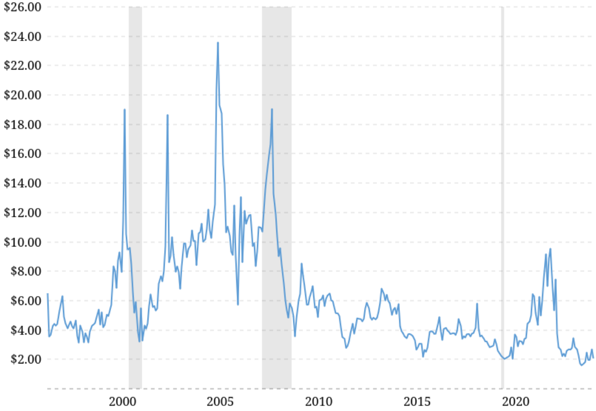


Macrotrends

There are lots of fluctuations because of political events etc.
Since 1970s oil prices are not rising systematically.

Is natural gas getting more expensive?

Inflation-adjusted data:



Macrotrends

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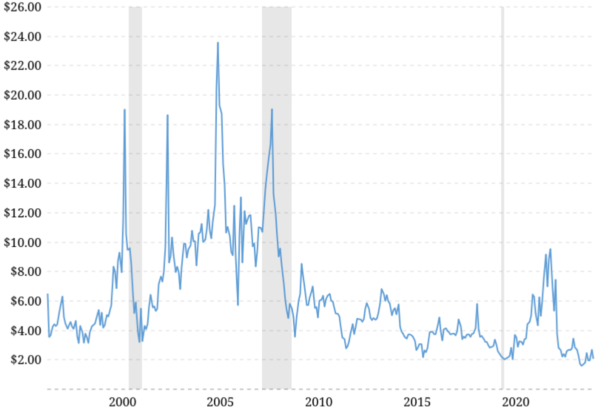
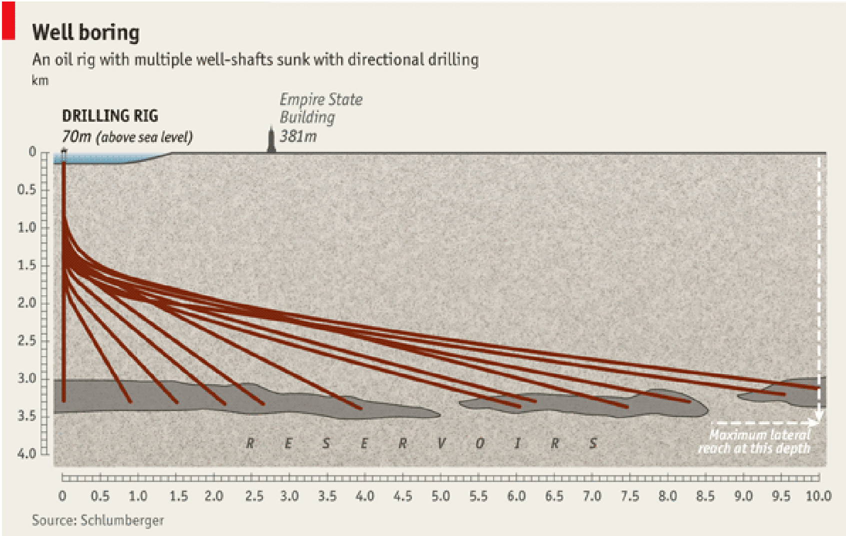


Macrotrends

Prices are not rising, thanks to mining technology like directional drilling and fracking.

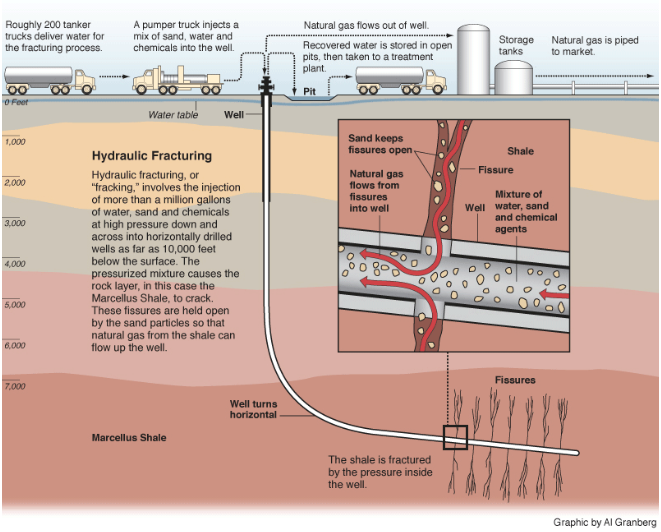
Directional drilling



horizontal and vertical scale in kilometers

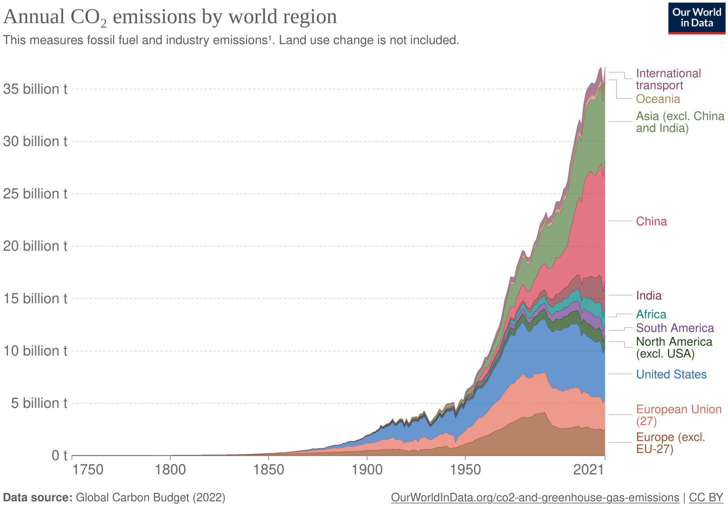
One rig can draw oil from a wide area.

Hydraulic fracturing



Fracking allows the extraction of Oil and Natural Gas from shale rocks.

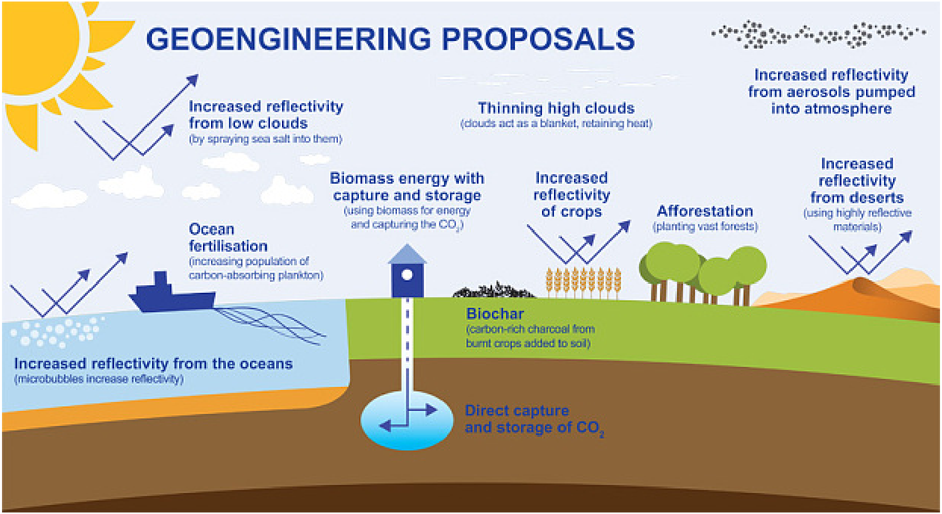
CO_2 emissions from world regions



1. Fossil emissions: Fossil emissions measure the quantity of carbon dioxide (CO_2) emitted from the burning of fossil fuels, and directly from industrial processes such as cement and steel production. Fossil CO_2 includes emissions from coal, oil, gas, flaring, cement, steel, and other industrial processes. Fossil emissions do not include land use change, deforestation, soils, or vegetation.

[Our World in Data]

Geoengineering



Daily Telegraph, UK

Geoengineering ideas

- Increase IR emissivity: remove GHG from the atmosphere
  - Plant more trees
  - Deploy crushed CO_2-absorbing rock, e.g. olivine
  - Thinning of Cirrus clouds (use seeds to make larger ice crystals)
  - Fertilization of oceans to encourage CO_2-absorbing microbes
  - Direct air capture and sequestration
- Decrease absorption fraction: reduce the heating effect of the sun
  - Aerosols in stratosphere ("fake volcanoes") or sulfur dioxide
  - Space mirrors
  - Increase reflectivity of low clouds
  - Increase surface reflection, e.g. from deserts or oceans

How can we reduce GHG emission?

(while still meeting rising energy needs)

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(while still meeting rising energy needs)

(1) Efficiency

On-demand electricity generation:

(2) "Clean Coal" (Carbon sequestration)
(3) Nuclear
(4) Geothermal

Intermittent electricity generation:

(5) Wind
(6) Solar
 (a) solar photovoltaic: convert sunlight directly to electricity
 (b) solar thermal: use the heat in sunlight

For intermittent approaches, need better *energy storage* technology.

Generating energy in an already stored form:

(7) Biofuels

(1) Efficiency

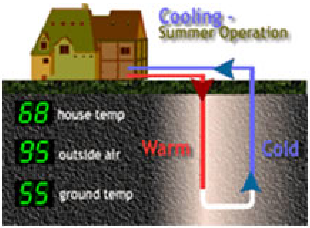
How can we use less energy and achieve the same goals?

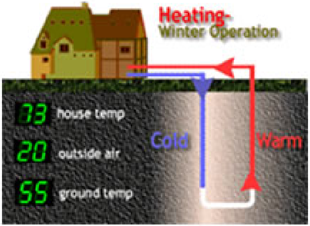
(1) Efficiency

How can we use less energy and achieve the same goals?

- More efficient fossil-fueled vehicles (fuel economy)
- More efficient heating/cooling of buildings,
  e.g. insulation, geothermal
- More efficient appliances (fridges, LED lighting, ...)
- More efficient electricity generation and distribution by utilities,
  e.g. "integrated gasification combined cycle" plants

Efficiency example: Geothermal heating/cooling





Temperature underground is always about 13 C (55 F).

In summer, heat pump uses "coolness" of underground earth (relative to hot outside air) to cool the house

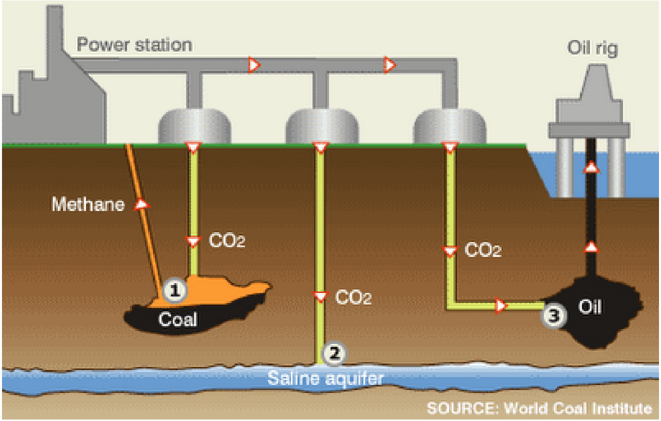
In winter, heat pump uses "warmness" of underground earth (relative to cold outside air) to warm the house

Exercise

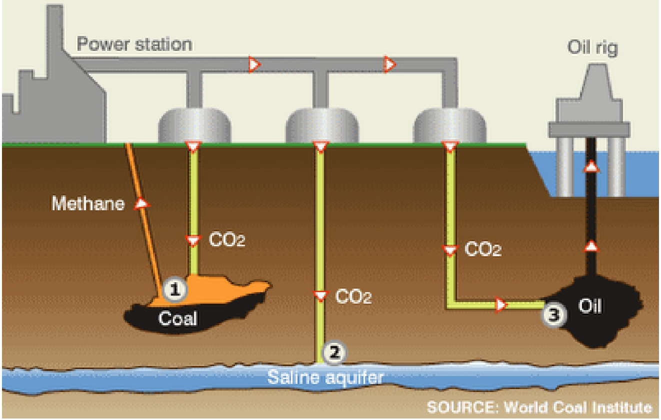
Suppose you have a choice between
(A) A natural gas home heating system with an efficiency of about 80%.
(B) An electrically powered geothermal heater with CoP=3, in a place where electricity is produced by burning natural gas.

Which choice creates less CO_2 per kWh of heat delivered to your house?

(2) Clean coal: carbon sequestration

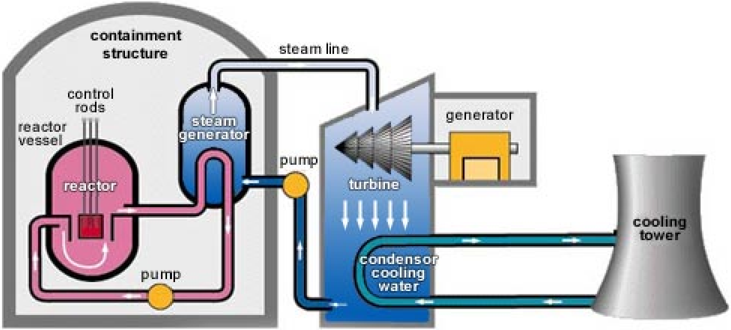


(2) Clean coal: carbon sequestration

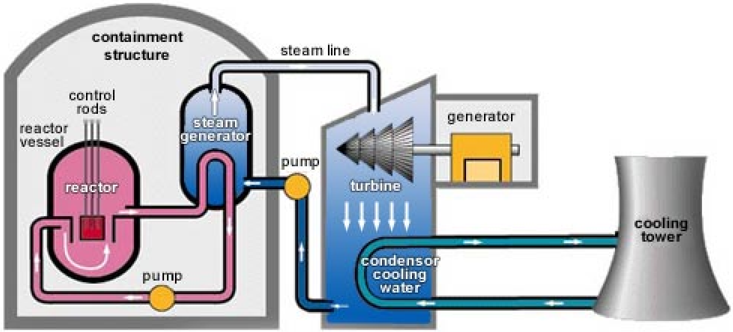


<u>Pro</u>: Developing countries can still use fossil fuels
<u>Con</u>: Makes the energy more expensive by 50 to 100%
possibility of disastrous CO_2 escape

(3a) Nuclear Fission Power



(3a) Nuclear Fission Power



Pro: On-demand power; known technology; can use it anywhere
Con: nuclear waste; public fear

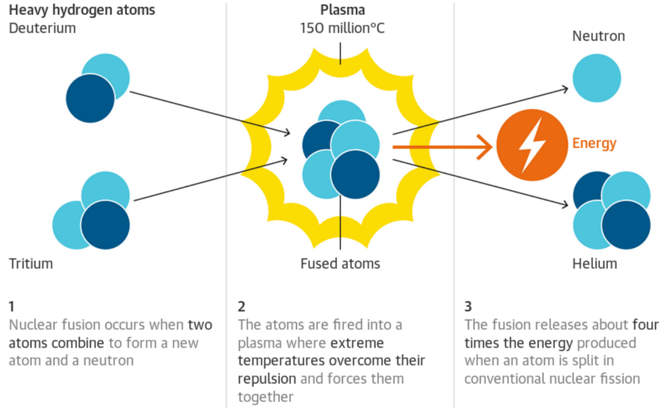
Maybe Thorium-type reactors, or Modular reactors?

Exercise

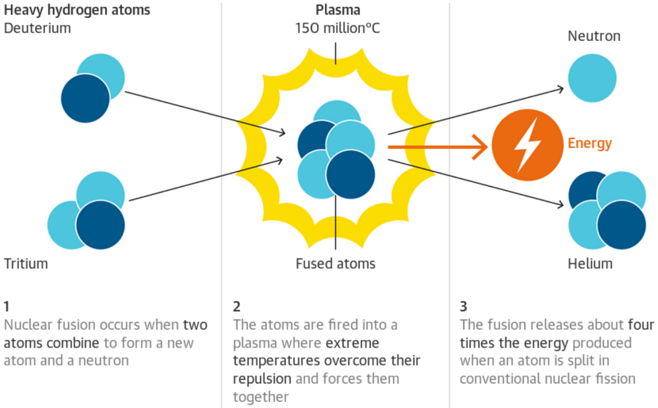
Estimate how much uranium would be needed to run a 1 GW power plant for a year. Assume the power plant is 30% efficient at turning the energy stored in uranium in to electricity.

(A) 100 kg (B) 10,000 ton (C) 1 ton (D) 100 ton

(3b) Nuclear fusion



(3b) Nuclear fusion

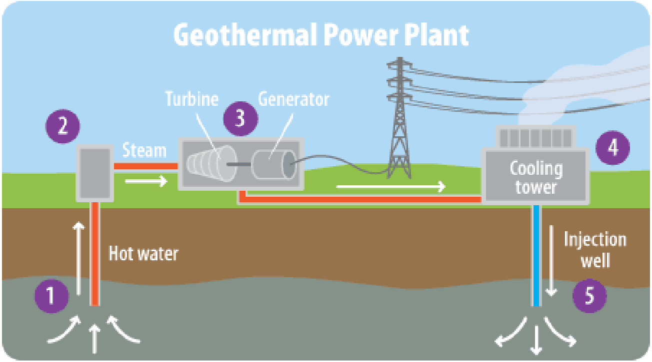


Pro: on demand power; can use it anywhere; no radioactive waste;
Con: not yet (ever?) economical.

(4) Geothermal electrical power

Different from geothermal heating of buildings!

Inject cool water into hot underground rocks, use resultant steam to drive turbines and generate electricity.



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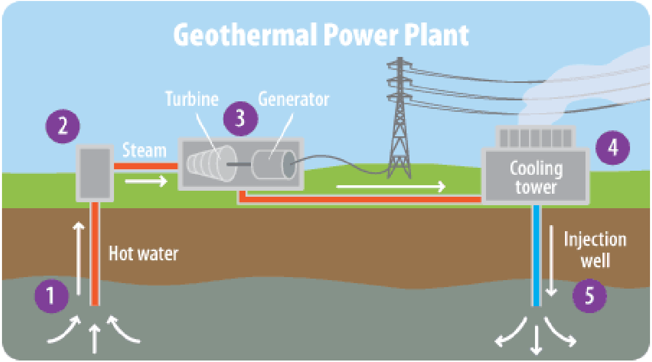

Pro: unlimited free resource; on demand;
Con: limited to volcanic areas (or deep drilling needed)
Need for efficient *energy transmission*

(5) Wind turbines

(5) Wind turbines

PRO: wind costs nothing

CON: intermittent; geographically limited; environmental impact

Need better *energy storage* and *long-range transmission*

(6a) Solar Photovoltaic

Directly converts sunlight into electricity.

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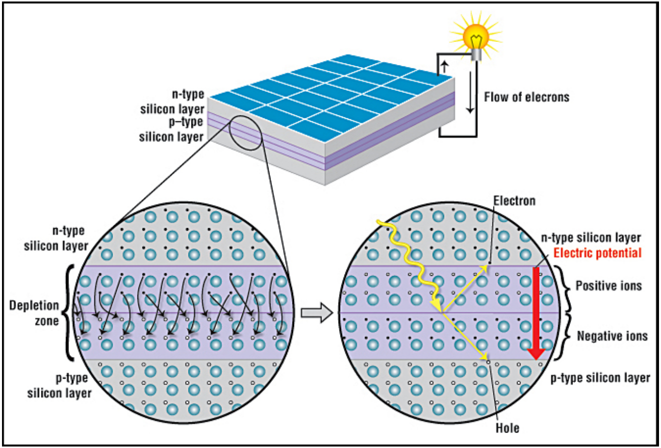
Directly converts sunlight into electricity.

PRO: sunlight is free; can be used on small or large scale

CON: intermittent, some geographic constraints

Need better *energy storage* and *long-range transmission*

How solar cells work



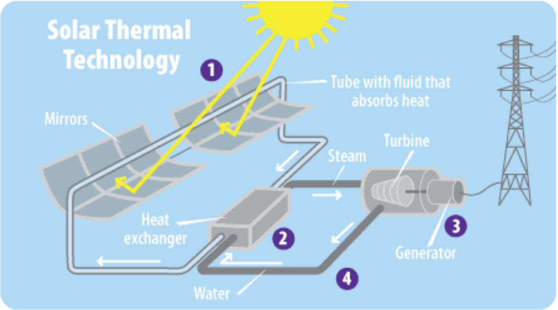
$$\text{Typical efficiency} = \frac{\text{electrical power out}}{\text{sunlight power in}} = 0.20 \quad (20\%)$$

Exercise

What is the cost of solar power, using typical solar panels, in terms of dollars per Watt of electrical power generating capacity (in full sunlight)?

(A) \$5/Watt (B) \$1/Watt (C) 25 ¢/Watt (D) 2.5¢/Watt

(6b) Solar Thermal: utility-scale electricity



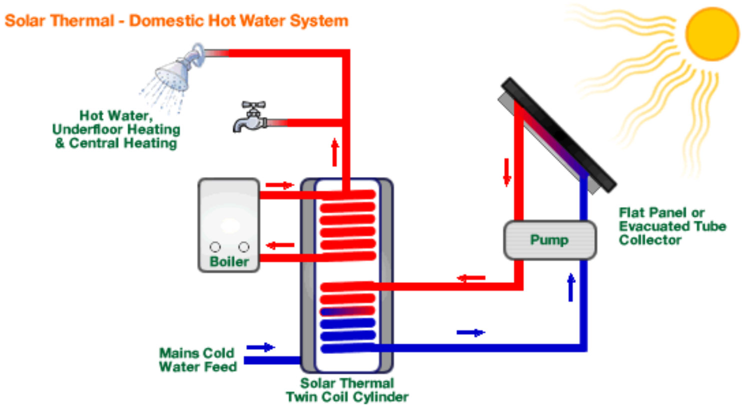
Sunlight is concentrated on pipes to heat water and make steam
Steam drives turbines to make electricity (it's a heat engine)

$$\text{Typical efficiency} = \frac{\text{electrical power out}}{\text{sunlight power in}} \approx 20\%$$

Solar Thermal example: Ivanpah

Ivanpah Solar Electric Generating System, opened Feb 2014.
Mirrors direct sunlight to heat steam in central towers, which generates electricity via turbines.
Power output is about 400 MW at peak.

(6c) Solar Thermal: domestic hot water



Heat from the sun acts as a booster, warming up the water so the domestic hot water system uses less utility-provided energy.

Exercise

What is the U.S.'s average rate of electrical power consumption?

(A) 1200 GW (B) 100 GW (C) 5 GW (D) 400 GW

Exercise

What is the U.S.'s average rate of electrical power consumption?

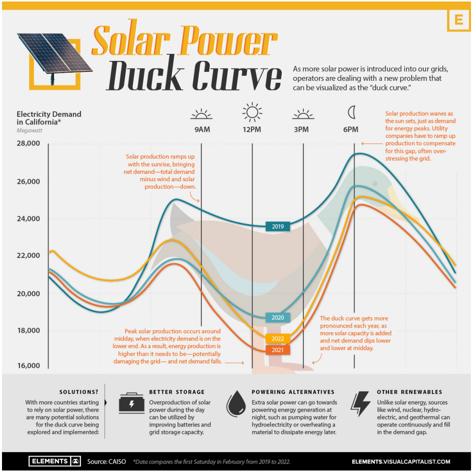
(A) 1200 GW (B) 100 GW (C) 5 GW (D) 400 GW

What area of solar panels that have 20% efficiency, and are in full sunlight about 6 hours/day, can provide the USA's average electrical power need?

(A) $(100\,\mathrm{km})^2$ (B) $(300\,\mathrm{km})^2$ (C) $(50\,\mathrm{km})^2$ (D) $(700\,\mathrm{km})^2$

A challenge for solar power

It distorts the net load on non-solar electricity generation plants, as seen in the “**Duck Curve**”.



- Solar produces most energy at midday when demand is lowest
- Solar stops producing as demand rises in late afternoon

Need *energy storage* to allow supply to track demand.

Exercise

How much energy would you have to store in order to power a small town of 10,000 houses for a day?

(A) 50 MWh (B) 50 kWh (C) 250 MWh (D) 250 kWh

Large-scale energy storage

If we could store large amounts of energy, we could make better use of *intermittent* energy sources (solar, wind).

Large-scale energy storage

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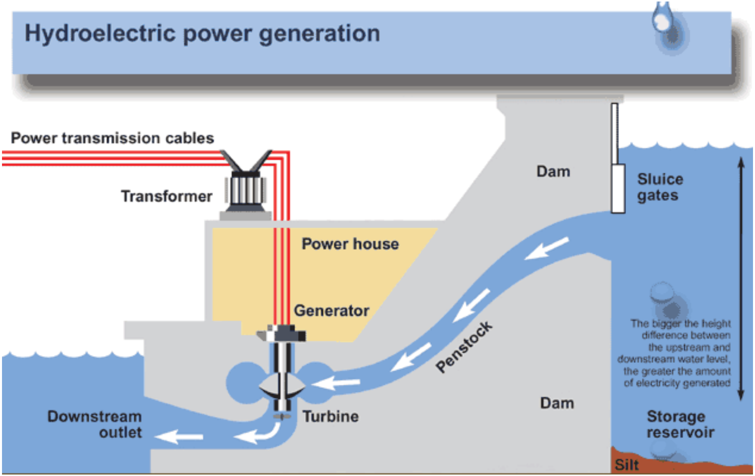
Storage Method	Energy Density (Joules/gram)	
gravity (hydroelectric, concrete)	1-3	(depends on height)
molten salt	$\sim$3	
compressed air	$\sim$100	
flywheel	$\sim$200	(can be 50 to 500 J/g)
lithium-ion battery	$\sim$400	(expensive to make)
hydrogen	110,000	(difficult to store)

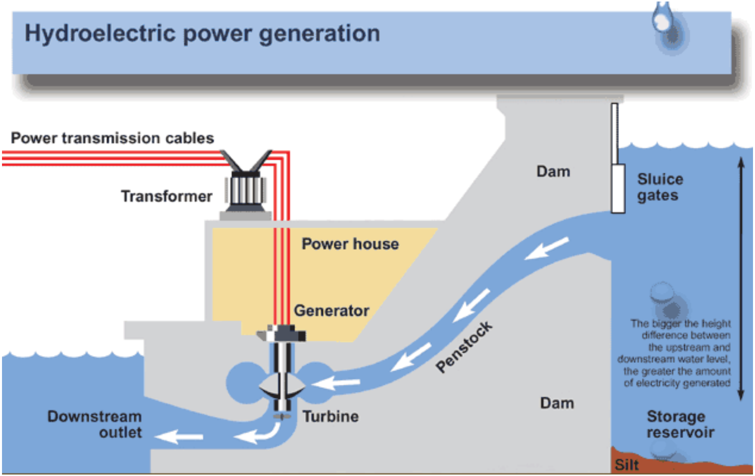
For comparison:

butter	30,000	
coal	30,000	
gasoline	40,000	
natural gas	50,000	
uranium-235	20,000,000	

Gravity storage: hydroelectric



Gravity storage: hydroelectric



PRO: simple, proven technology; turbines 80-90% efficient

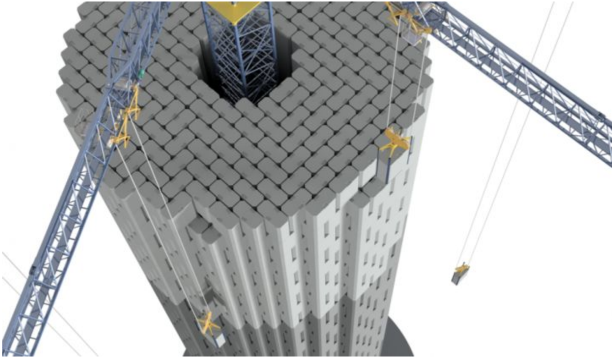
CON: low energy density; geographically limited (need lots of water)

Taum Sauk reservoir failure

Dec 14 2005, 5:12am, reservoir failed, leaking 4 million tons in 12 minutes.

Taum Sauk reservoir flood path

Gravity storage: concrete blocks



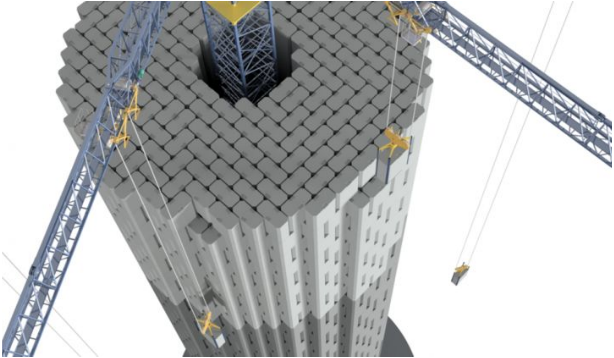
When surplus energy is available: cranes use energy to lift blocks.

When energy is needed: cranes lower blocks, generating electricity via turbines.

Energy (J) stored by raising a mass M (kg) though height h (m) is

$$E = Mgh \qquad (g = 10\,\mathrm{J\,kg^{-1}m^{-1}})$$

Gravity storage: concrete blocks



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Energy (J) stored by raising a mass M (kg) though height h (m) is

$$E = Mgh \qquad (g = 10\,\mathrm{J\,kg^{-1}m^{-1}})$$

PRO: simple, proven technology; elec motors $\sim$ 80% efficient

CON: low energy density—need lots of concrete.

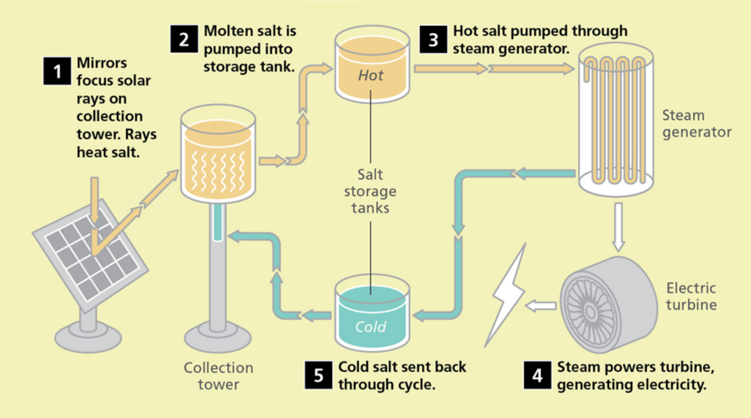
Exercise

Roughly what mass of concrete blocks would we need if we wanted to store enough energy to power a small town of 10,000 houses for a day? The blocks can be raised and lowered by 100 m.

(A) 1 ton (B) 1 million tons (C) 10,000 tons (D) 100 tons

Thermal energy storage: molten salt

Heat energy is stored in insulated tanks of melted salt at 300–800 C



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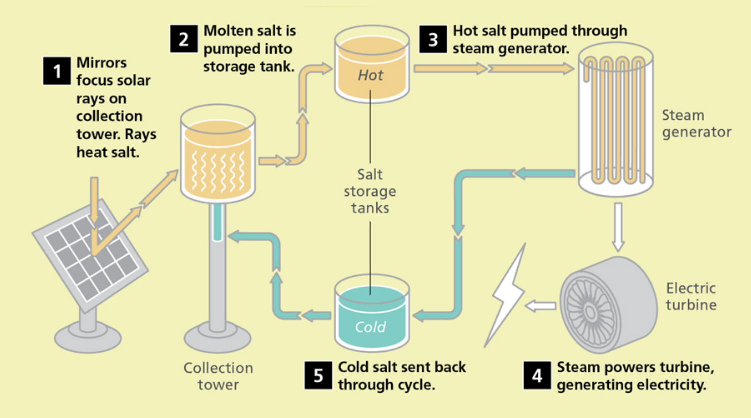

PRO: simple technology; cheap; can be used anywhere

CON: low energy density (need lots of salt); efficiency...?

Exercise

Roughly what is the maximum theoretical efficiency of a molten salt energy storage facility that uses salt at 600 C?

(A) 70% (B) 90% (C) 40% (D) 15%

Exercise

Roughly what is the maximum theoretical efficiency of a molten salt energy storage facility that uses salt at 600 C?

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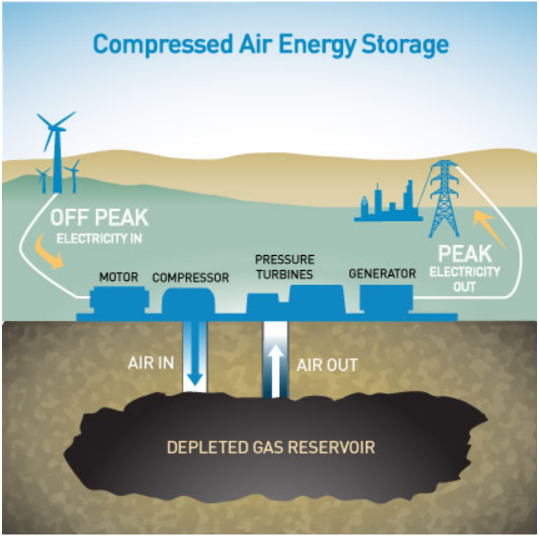
In practice, efficiency of molten salt storage $\approx$ 40%

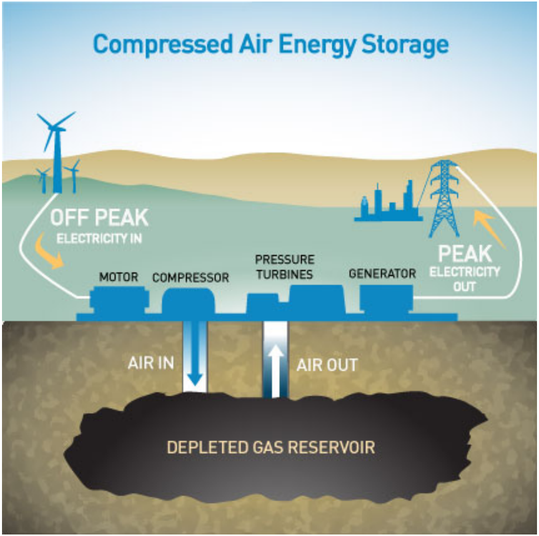
Compressed air energy storage



When surplus energy is available: pumps push air in to reservoir

When energy is needed: air exits reservoir via turbines

Compressed air energy storage



When surplus energy is available: pumps push air in to reservoir

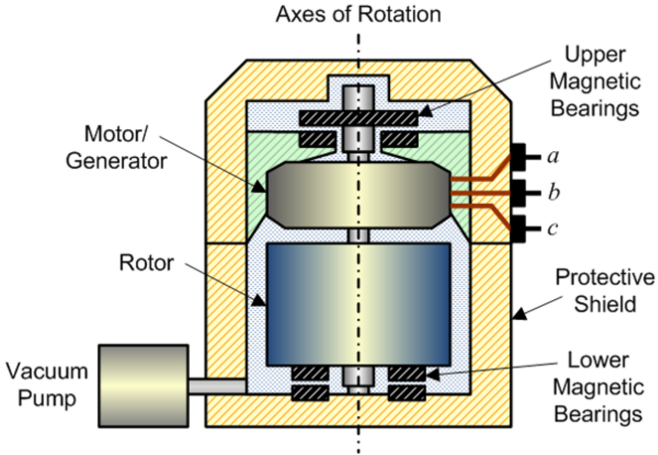
When energy is needed: air exits reservoir via turbines

PRO: simple technology (cheap); adiabatic storage can be 70% efficient

CON: geographically limited: need large natural caverns

Kinetic energy storage: flywheel

Fast-rotating flywheel stores kinetic energy, $E = \frac{1}{2}Mv^2$



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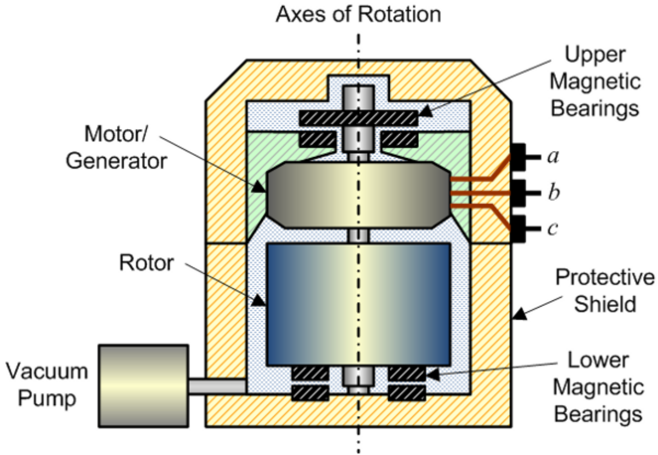


PRO: simple technology; can power up/down quickly; efficiency $\sim 90\%$
CON: low energy density: need a huge flywheel or many flywheels

Chemical energy storage: batteries

Nova Power Bank (near Los Angeles)

projected energy capacity: 2700 MWh

projected power output: 680 MW

Chemical energy storage: batteries

Nova Power Bank (near Los Angeles)

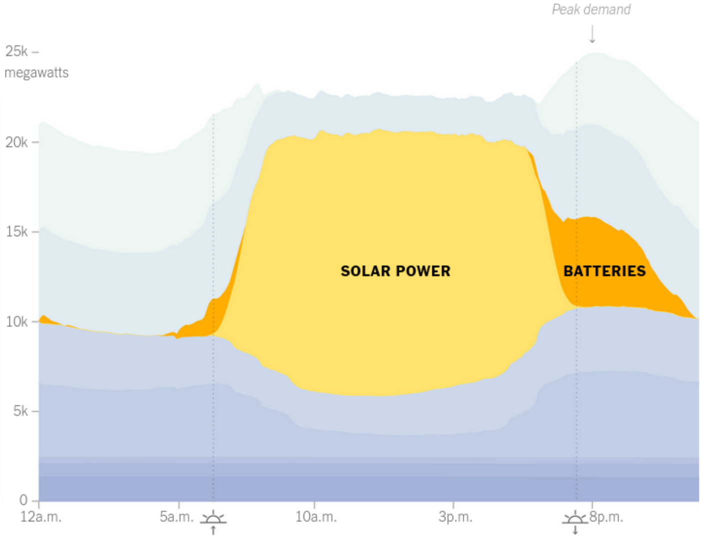
projected energy capacity: 2700 MWh

projected power output: 680 MW

PRO: proven technology; high (enough) energy density; useable anywhere; efficiency $\sim 70\%$
CON: expensive (zinc-hybrid is cheaper than lithium);
may degrade after many charging cycles (but not "flow batteries")

Batteries vs the duck curve

California electricity production, Apr 2024



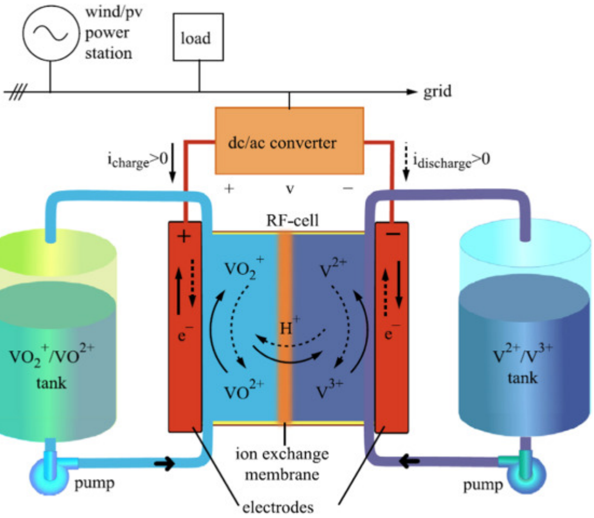
NYT, Aug 2024

Exercise

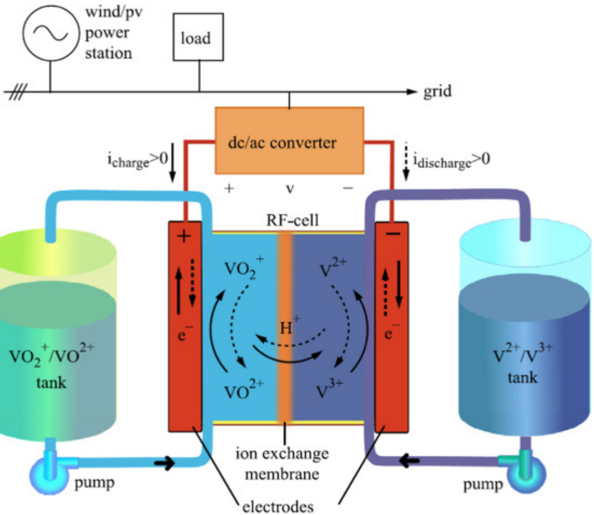
Estimate the mass of lithium-ion batteries in California's energy storage system.

(A) 2 million tons (B) 700,000 tons
(C) 200,000 tons (D) 70,000 tons

Flow batteries



Flow batteries



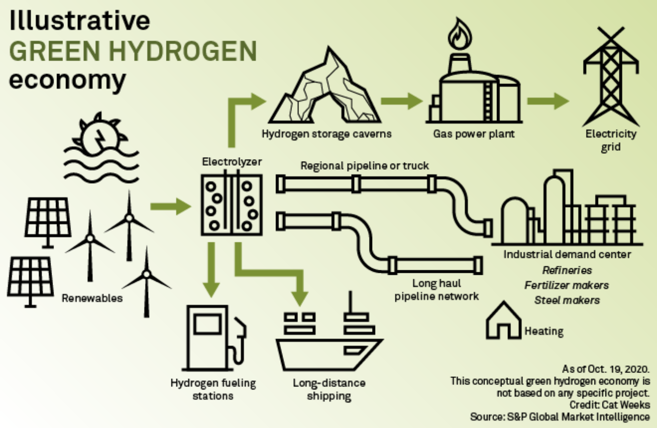
PRO: scalable (capacity and power, independently),
safe, charge doesn't leak, durable (many cycles)
CON: low energy density ($\sim 100\,\mathrm{J/g}$), more expensive (for now)

Dalian flow battery

Location:	Dalian, NE China
Energy Capacity:	400 MWh
Power:	100 MW

Chemical energy storage: hydrogen

Use hydrogen to store excess energy from renewable sources.



electrolysis:
H_2O + energy
$\rightarrow H_2 + O$

efficiency is $\sim 40\%$ but the energy would have been wasted otherwise.

Chemical energy storage: hydrogen

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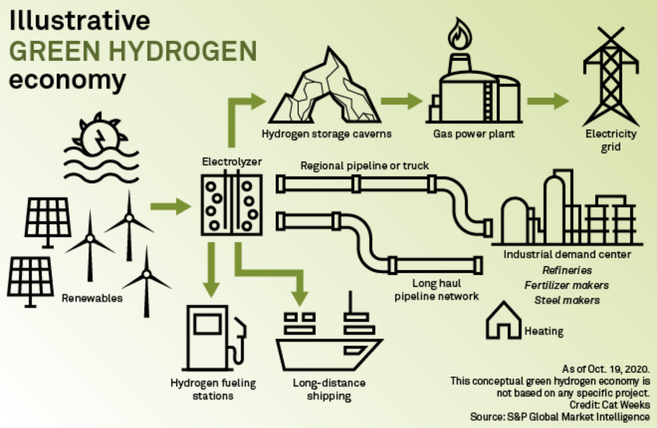


electrolysis:
H_2O + energy
$\rightarrow H_2 + O$

efficiency is $\sim 40\%$ but the energy would have been wasted otherwise.

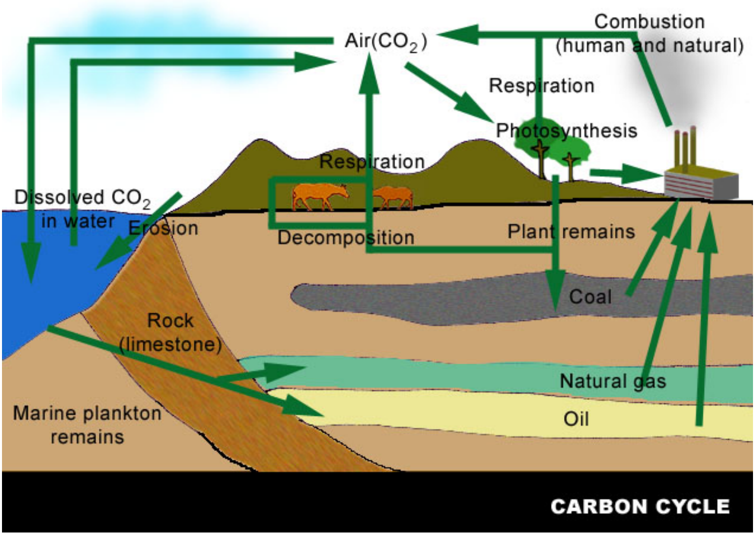
PRO: known technology; usable at large scale, long time, e.g summer$\rightarrow$ winter; energy can be piped or transported to other locations.
CON: needs large secure caverns, or some new material that can absorb hydrogen; expensive for now.

Hydrogen storage in Utah

Example: Advanced Clean Energy Storage ("ACES") in Delta, Utah.

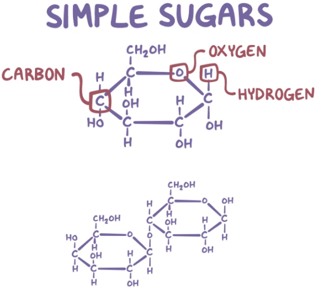
Will make hydrogen from renewable energy and store it in salt dome caverns.
Plans to store 150GWh of energy.

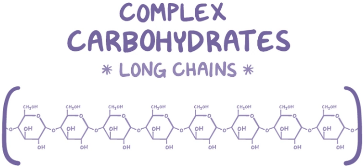
(7) Biofuels: The carbon cycle



The idea: Carbon in biofuels comes from our current atmosphere via photosynthesis. So burning them does not increase atmospheric CO_2.

Carbohydrates





Sugar: mono- or di-saccharides

Starch: are polycaccharides with 10 or more units.

Oil: long chains of CH_2 units

Biofuels: pro and con

Biofuels: pro and con

Advantages:

- Renewable
- Burning the fuel does not add *net* CO_2 to the atmosphere
- Can be a liquid fuel: very energy dense, convenient for transportation

Biofuels: pro and con

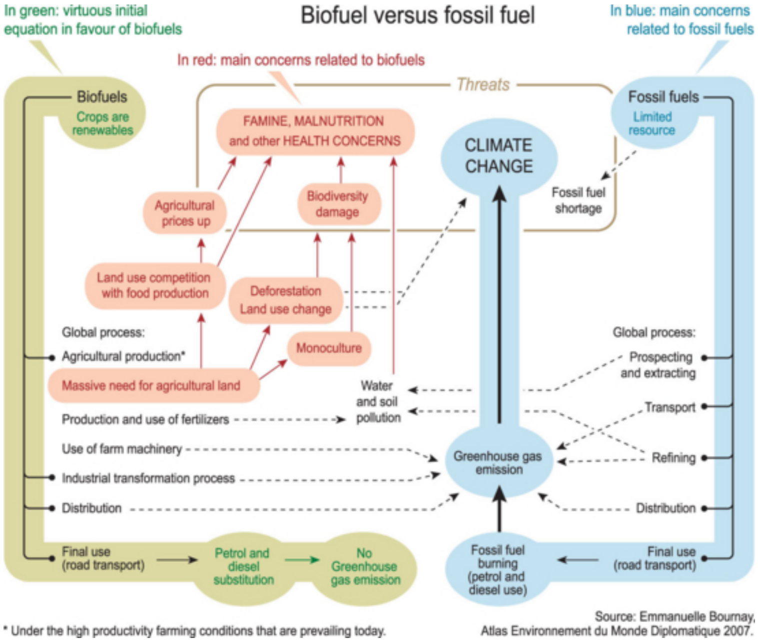
Advantages:

- Renewable
- Burning the fuel does not add *net* CO_2 to the atmosphere
- Can be a liquid fuel: very energy dense, convenient for transportation

Disadvantages:

- Competes with food crops for resources
- Production can emit greenhouse gases

Biofuel vs. fossil fuel

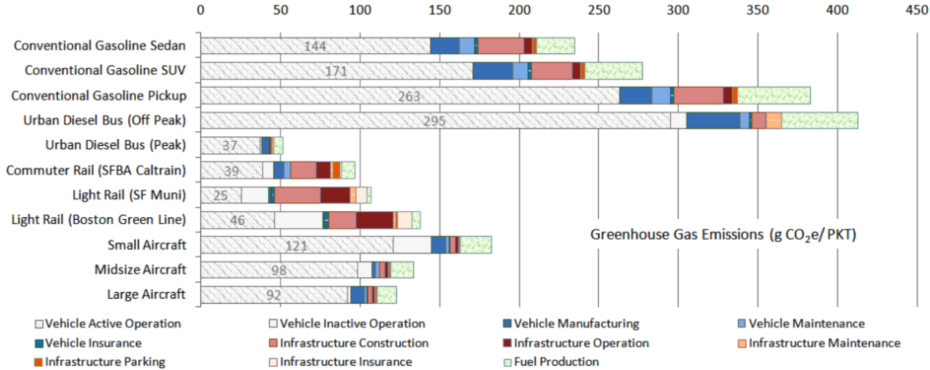


A better biofuel: Cellulosic Ethanol

Turn *non*-food plants (grass, wood etc) into liquid fuel.

Environmental impact of transportation

GHG emission per passenger, per kilometer traveled.



Environ. Res. Lett. 4 024008 (2009)

Aircraft are not so bad. Buses are only good if they are full.

Cap and trade

A market-based mechanism for using natural economic incentives to lower emissions.

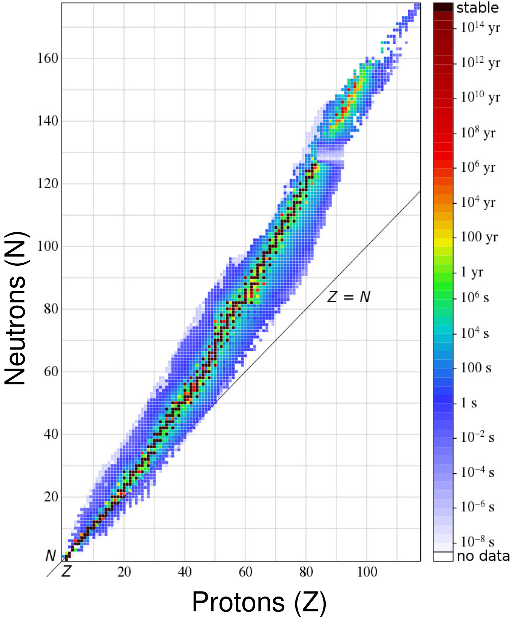
- Explicitly mandated by Kyoto Protocol (expired 2012)
- Not mandated but encouraged by Paris agreement 2015
- Rules agreed at Glasgow 2021

  - Each country has an allowed level ("cap") of GHG emissions
    - If it emits less, it can sell the unused portion to other countries
    - If it emits more, it must buy credits from other countries
  - Countries that find economic ways to reduce GHG emission can make money
  - Countries that earn a lot of money from GHG emitting activities can continue as before, but have to pay for doing that.

Nuclear energy and radiation

- What is radiation?
- How do nuclear power plants and nuclear weapons release so much energy?
- What is radioactive waste?
- How do we evaluate the health effects of radioactivity?

Stable and unstable nuclei



- Only isotopes with the right admixture of neutrons (black squares) are stable.
- Lighter elements ($Z \lesssim 20$) prefer $N = Z$.
- Heavier elements need extra neutrons to be stable.
- Beyond lead ($Z > 82$) all elements are unstable though some have very long lifetimes.

Some stable and unstable isotopes

Name	symbol	Z	N	$A = Z + N$	Abundance	Lifetime
Hydrogen	${}^1_1\text{H}$	1	0	1	99.985%	∞?
Deuterium	${}^2_1\text{H}$	1	1	2	0.015%	∞?
Tritium	${}^3_1\text{H}$	1	2	3	tiny	12 years

Some stable and unstable isotopes

Name	symbol	Z	N	$A = Z + N$	Abundance	Lifetime
Hydrogen	${}^{1}_{1}H$	1	0	1	99.985%	∞?
Deuterium	${}^{2}_{1}H$	1	1	2	0.015%	∞?
Tritium	${}^{3}_{1}H$	1	2	3	tiny	12 years
Carbon-12	${}^{12}_{6}C$	6	6	12	99%	∞?
Carbon-13	${}^{13}_{6}C$	6	7	13	1%	∞?
Carbon-14	${}^{14}_{6}C$	6	8	14	tiny	5700 years

...

Some stable and unstable isotopes

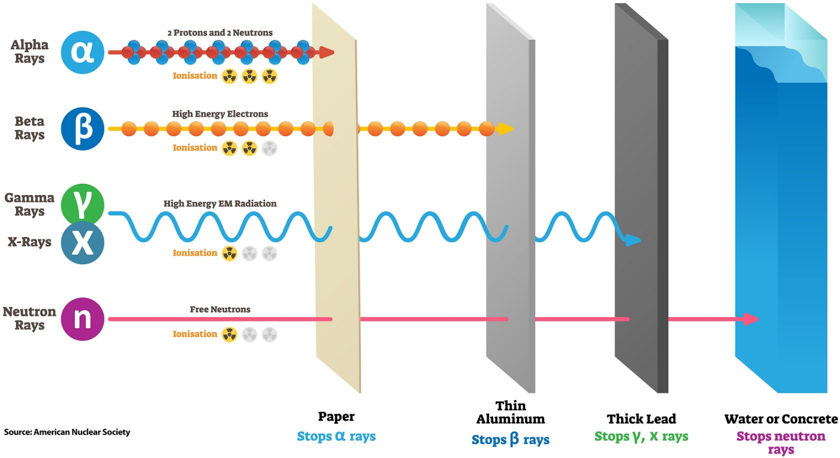
Name	symbol	Z	N	$A = Z + N$	Abundance	Lifetime
Hydrogen	${}^{1}_{1}H$	1	0	1	99.985%	∞?
Deuterium	${}^{2}_{1}H$	1	1	2	0.015%	∞?
Tritium	${}^{3}_{1}H$	1	2	3	tiny	12 years
Carbon-12	${}^{12}_{6}C$	6	6	12	99%	∞?
Carbon-13	${}^{13}_{6}C$	6	7	13	1%	∞?
Carbon-14	${}^{14}_{6}C$	6	8	14	tiny	5700 years
...						
Uranium-238	${}^{238}_{92}U$	92	146	238	99.3%	5 billion yrs
Uranium-235	${}^{235}_{92}U$	92	143	235	0.7%	0.7 billion yrs

Exercise

How could you make a nucleus of ^{12}C from nuclei of ^{1}H and ^{4}He?

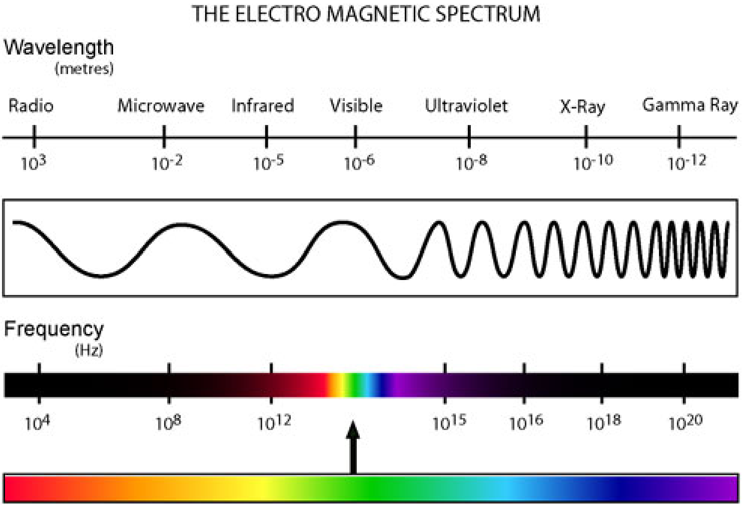
(A) one ^{4}He nucleus and some ^{1}H nuclei
(B) two ^{4}He nuclei and some ^{1}H nuclei
(C) three ^{4}He nuclei and no ^{1}H nuclei
(D) four ^{4}He nuclei and no ^{1}H nuclei

Types of radiation

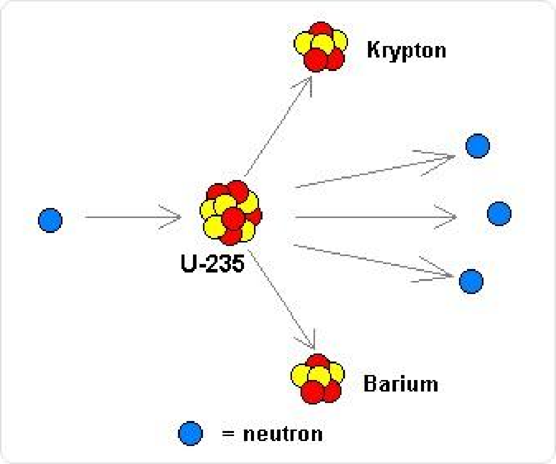


The spectrum of electromagnetic radiation

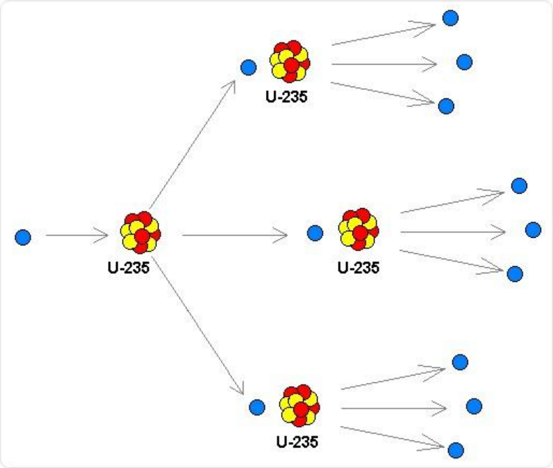
$$\boxed{c = f\lambda}$$



Induced fission of ^{235}U nucleus



Nuclear fission chain reaction



Exercise

How many ^{235}U nuclei are there in 1 kg?

(A) 10^{23} (B) 10^{24} (C) 10^{12} (D) 10^{14}

Exercise

How many ^{235}U nuclei are there in 1 kg?

(A) 10^{23} (B) 10^{24} (C) 10^{12} (D) 10^{14}

How much energy, in terms of the equivalent amount of TNT, is released in the fission of 1 kg of ^{235}U?

(A) 2 million tons of TNT
(B) 2 tons of TNT
(C) 20,000 tons of TNT
(D) 200 tons of TNT

Exercise

How many ^{235}U nuclei are there in 1 kg?

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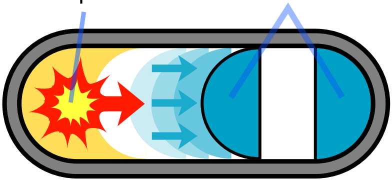
(A) 2 million tons of TNT
(B) 2 tons of TNT
(C) 20,000 tons of TNT
(D) 200 tons of TNT

Estimate how many fission steps would it take to fission all the nuclei in 1 kilogram of ^{235}U if each nuclear fission event causes two additional nuclear fission events.

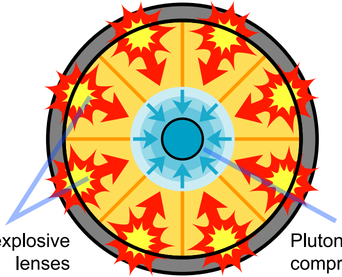
(A) 10^{12} (B) 10^{6} (C) 10^{4} (D) 100

Nuclear fission bomb



Gun-type assembly method

used on Hiroshima, 1945

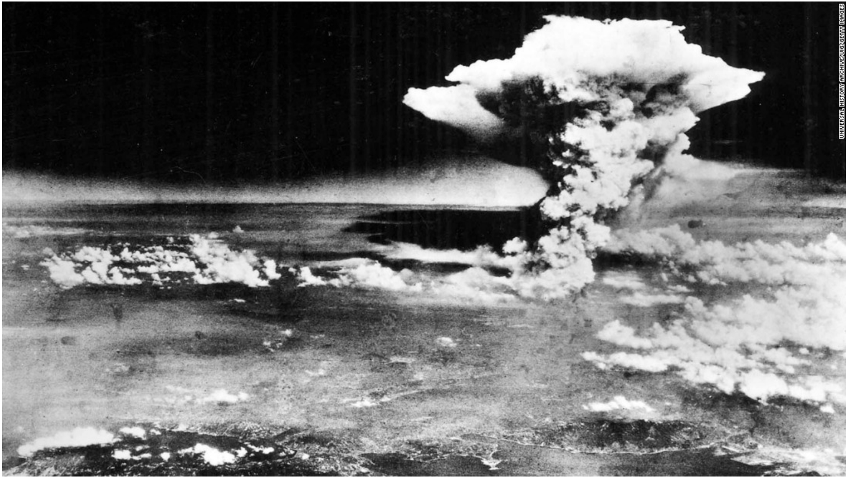


Implosion assembly method

used on Nagasaki, 1945

Ground-level damage in Hiroshima

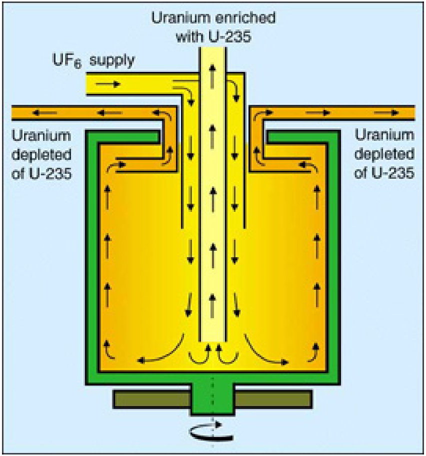
Fallout: air burst over Hiroshima



In an air burst, most fission fragments are carried up and away by thermal convection ("mushroom" cloud).

Uranium-235 separation

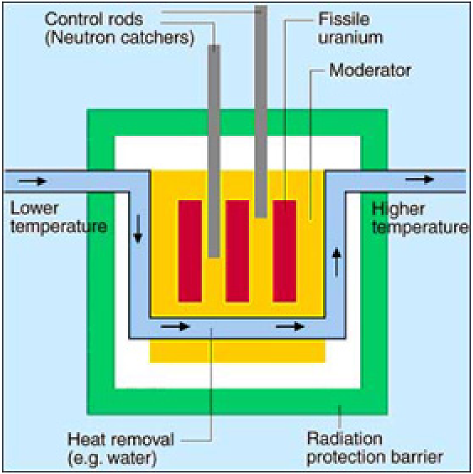
Uses uranium hexafluoride UF_6



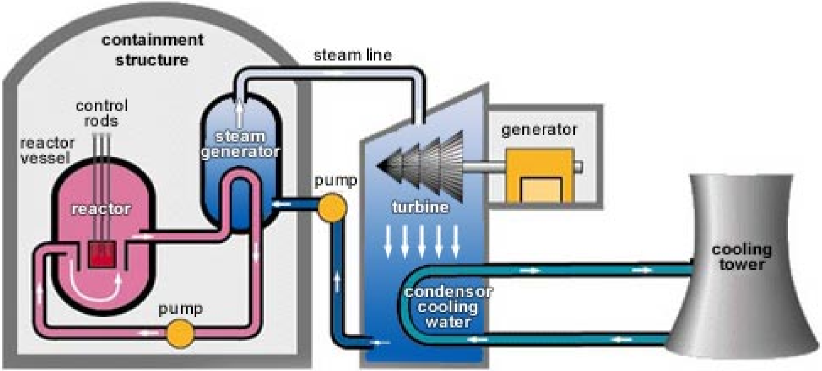
Heavier atoms are pulled more towards the outside of the rotating cylinder, so the inner region has a slightly higher concentration of ^{235}U.

Nuclear reactor 1

Extracting heat from sustained fission in Uranium fuel: cool water in, hot water out (under high pressure)



Nuclear reactor 2

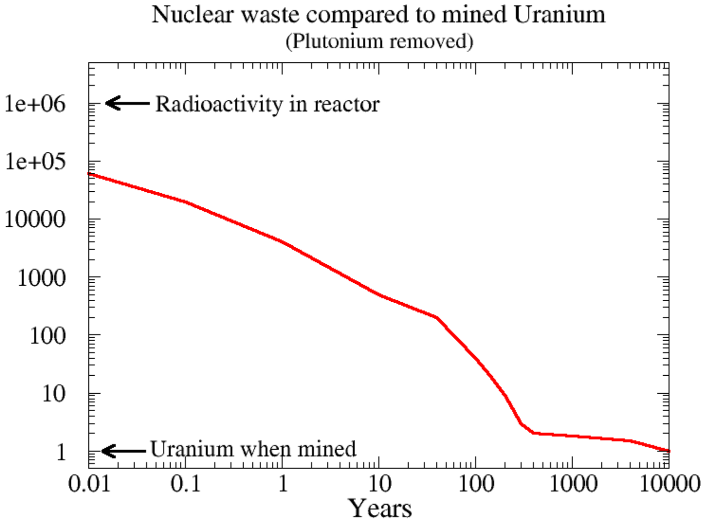


Exercise

What would happen to a nuclear reactor if the moderator leaked out while the reactor was running?

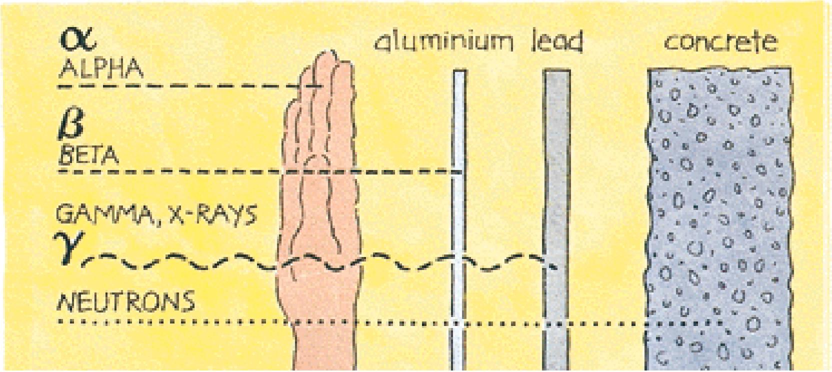
(A) the chain reaction would stop
(B) the fission fragments would recombine to form isotopes of uranium
(C) the chain reaction would continue
(D) the reactor would explode

Radioactivity of reprocessed nuclear waste



After a few hundred years it is only a few times more radioactive than the ore from which Uranium is mined.

Types of radiation



Radiation damage scale

Radiation damage to living tissue is measured in Sievert.
Older unit was rem: $100\,\text{rem} = 1\,\text{Sievert}$; $1\,\text{rem} = 10\,\text{mSv}$

1 Sv (whole-body) is the damage from 200 billion gamma rays going through each cm^3 of your body.

Short-term effects: radiation sickness (only from high doses)
Long-term effects: increased cancer risk

Short term: radiation sickness

Whole-body acute dose	Resulting radiation sickness
< 1 Sv	does not cause short-term illness
1-2 Sv	nausea, loss of hair, rarely fatal if treated
3-5 Sv	50% chance of death in 60 days (if untreated)
> 10 Sv	incapacitated within 1-2 hours, probable death

So LD50 for radiation is 3 Sv to 5 Sv full-body acute dose.

("acute" means "all at once")

Long term: increased cancer risk

Extra Risk = (whole-body effective dose) / (25 Sv) *

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Activity	Associated whole-body ("effective") radiation dose	
Background radiation	0.35 μSv/hr	cancer prob
(cosmic rays, rocks, etc)	0.01 mSv/day	
	3 mSv/yr	+0.00012/yr
Denver background	4 mSv/yr	+0.00016/yr

Long term: increased cancer risk

$\text{Extra Risk} = (\text{whole-body effective dose}) / (25 \text{ Sv})$ *

Activity	Associated whole-body ("effective") radiation dose	
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(cosmic rays, rocks, etc)	0.01 mSv/day	
	3 mSv/yr	$+0.00012$/yr
Denver background	4 mSv/yr	$+0.00016$/yr
1 Dental X-ray	0.005 mSv	$+2 \times 10^{-7}$
1 Intercontinental flight	0.03 mSv	$+1 \times 10^{-6}$
1 Mammogram	0.4 mSv	$+0.000016$
1 Full-body CT scan	20 mSv	$+0.0008$
Maximum expected for neighbors of Fukushima reactor in 2011	20 mSv	$+0.0008$

* According to the Linear Hypothesis

For more examples see `http://www.xkcd.com/radiation/`

Exercise

Suppose about half of the undergrads at WashU (about 3000 people) have mammograms. According to the LH, how many extra cancers does this cause?

(A) about 10 (B) 1-2 (C) less than 1 (D) 120

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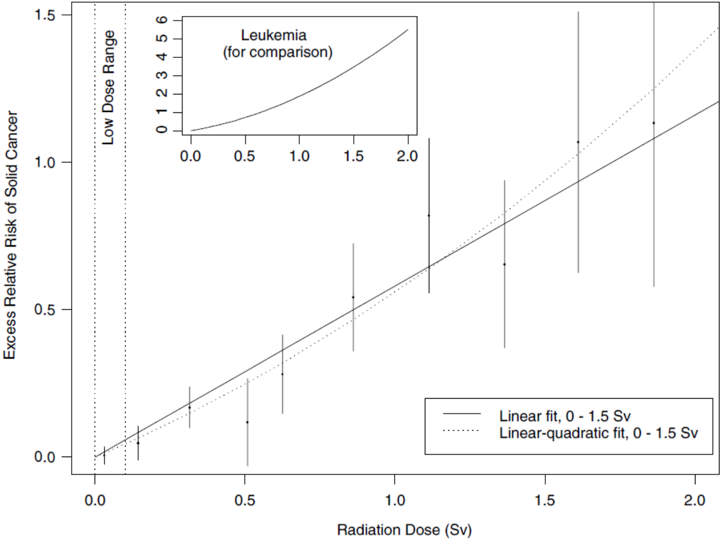
How many miles of driving has the same death risk as a mammogram (0.4 mSv whole body equivalent)?
Assume: Linear Hypothesis, and driving causes 1.2×10^{-8} deaths per mile driven (1 death per 80 million miles).

(A) 700,000 miles (B) 33 miles
(C) 1300 miles (D) 700 miles

Cancer risk from low-level radiation

Japanese atomic bomb survivor data



National Academy Study of Radiation Health Risks, 2006

http://books.nap.edu/catalog/11340.html