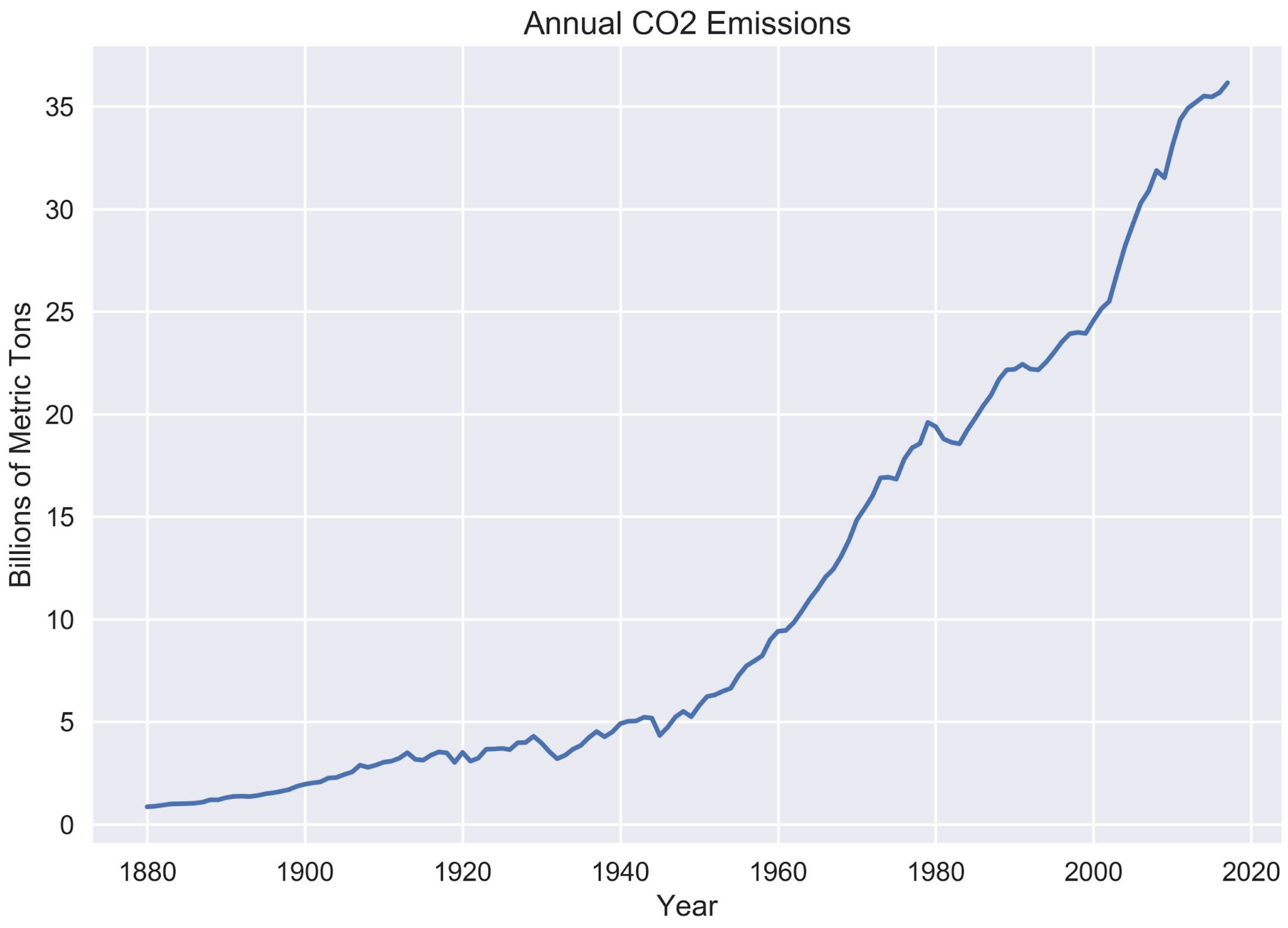
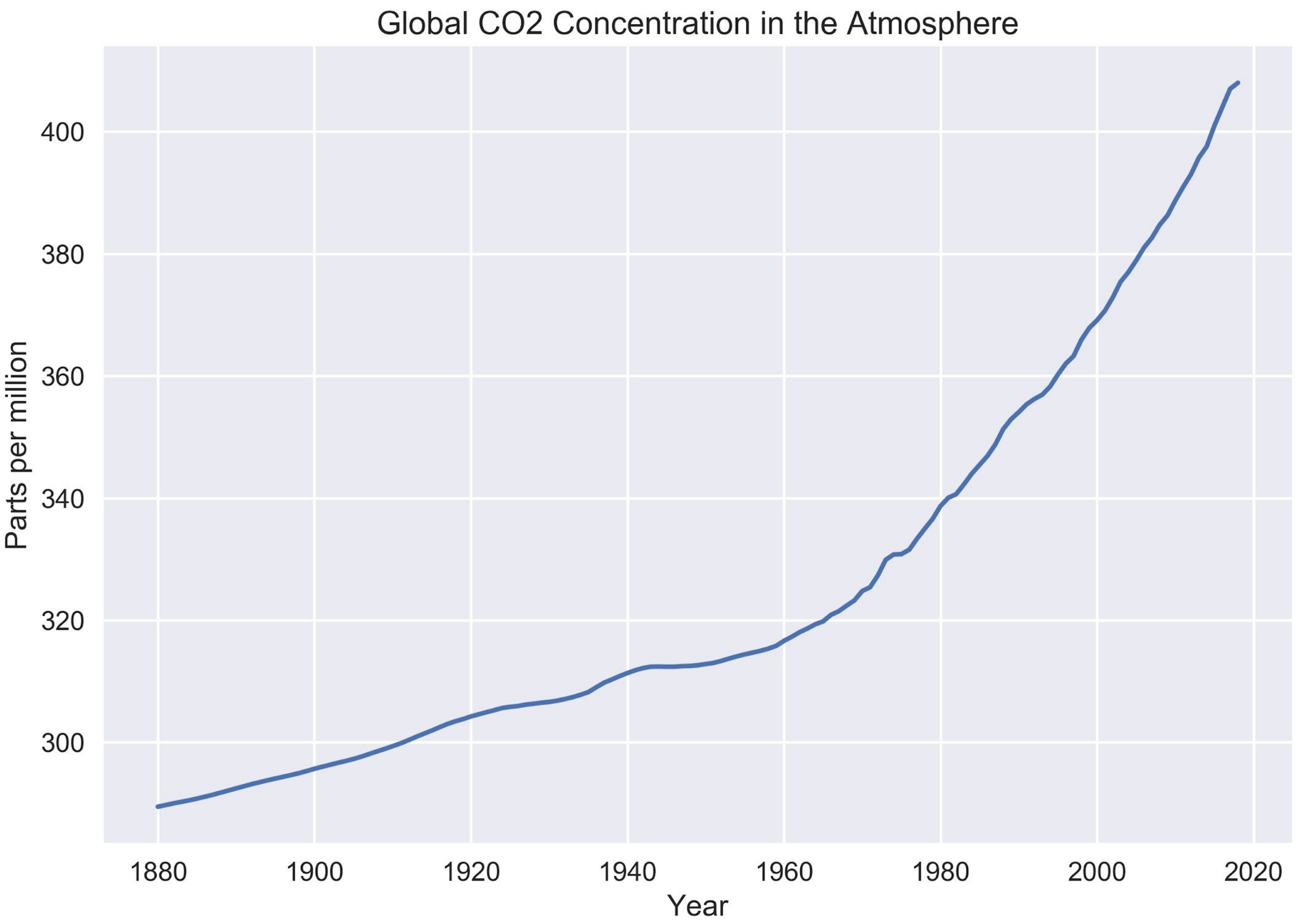
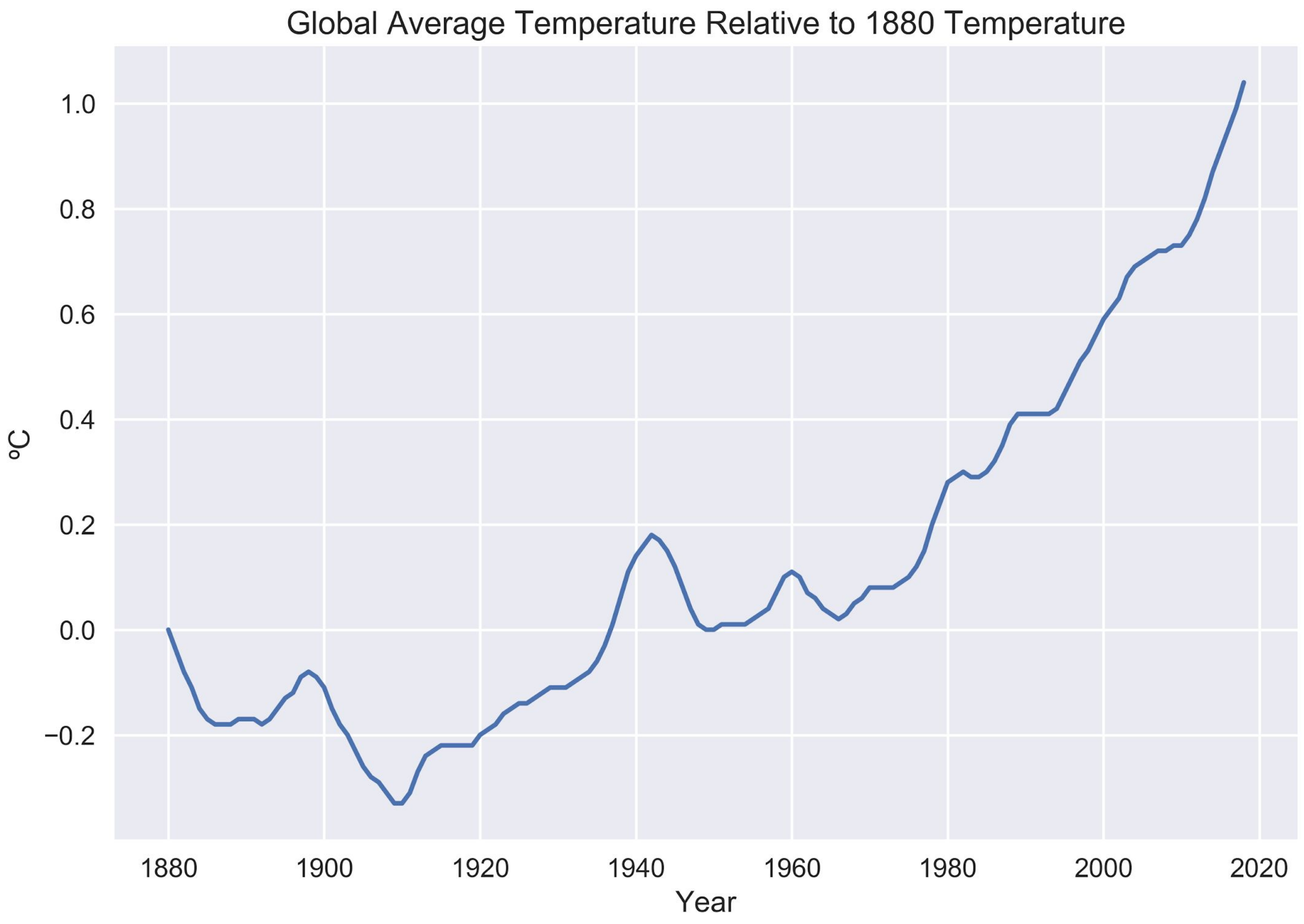
Climate change and the science behind emissions

Jesse Murray



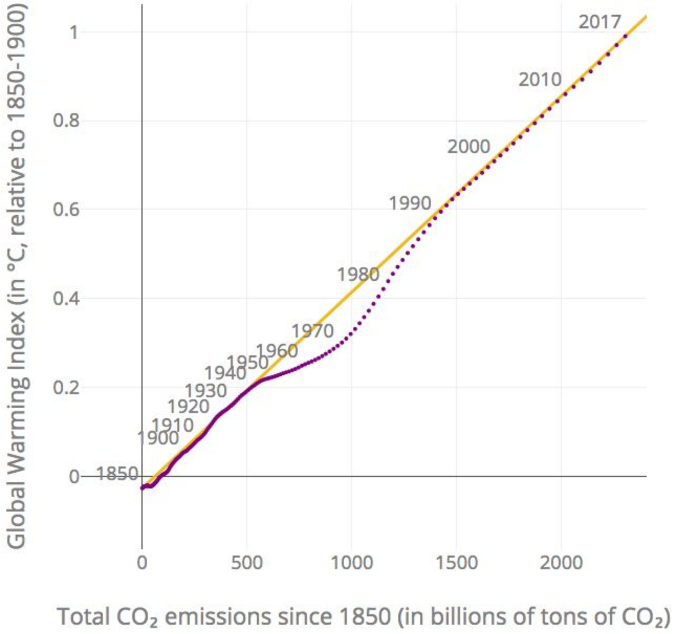
Annual CO2 Emissions
Billions of Metric Tons
0
5
10
15
20
25
30
35
1880
1900
1920
1940
1960
1980
2000
2020
Year


Global CO2 Concentration in the Atmosphere
Parts per million
300
320
340
360
380
400
1880
1900
1920
1940
1960
1980
2000
2020
Year



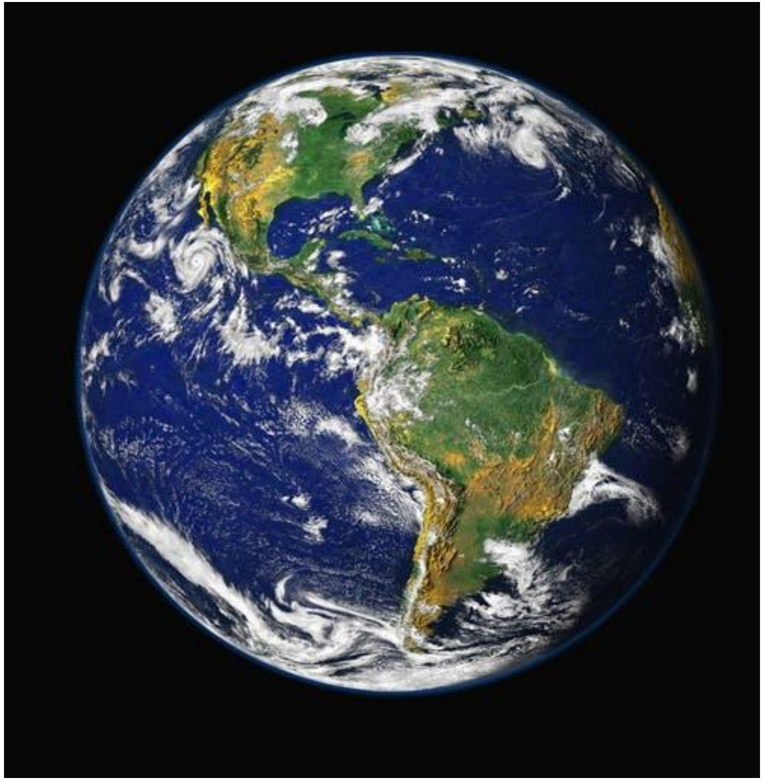
Global Average Temperature Relative to 1880 Temperature
°C
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
1880
1900
1920
1940
1960
1980
2000
2020
Year

Linear relationship between cumulative emissions and temperature rise



Going over 1.5 ºC should be **unacceptable** to us

- Destruction of ecosystems (especially polar, mountainous, and coral)
- Lower crop yields, leads to famine
- Displacement of people



How do we prevent going over 1.5ºC?

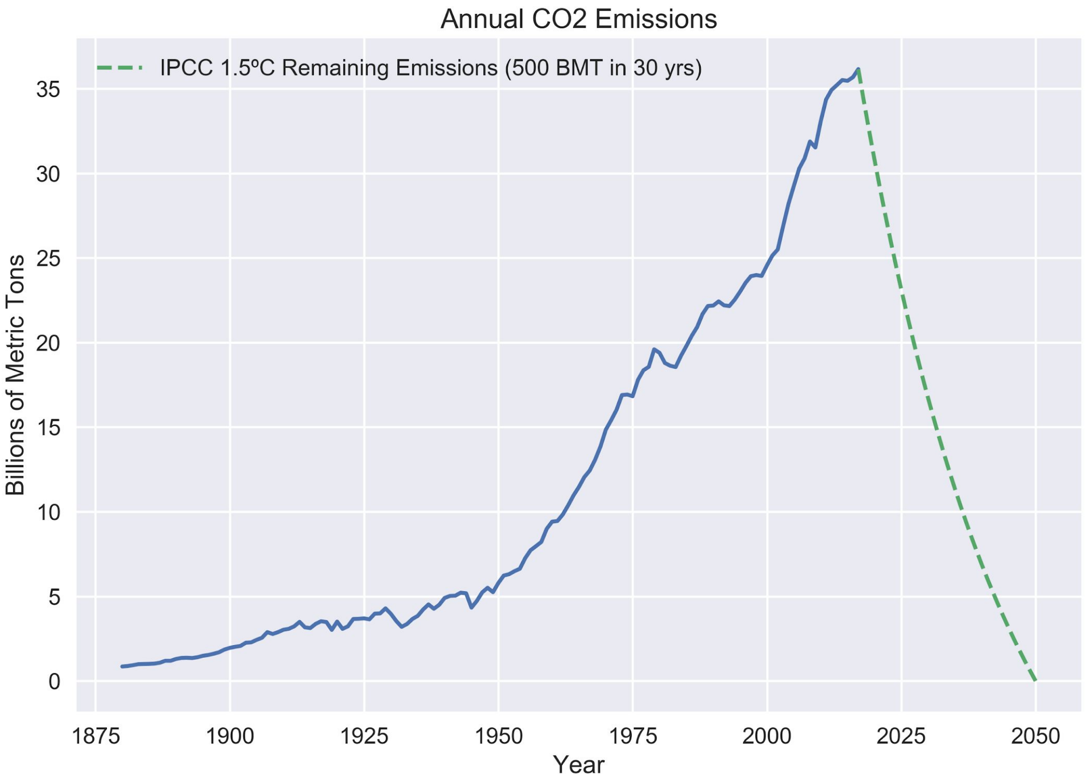
Most attention has gone towards an **emissions-only** approach

Through this approach:

- Only 500 billion metric tons can be emitted in the next 30 years
- **Zero emissions** by 2050

(IPCC)

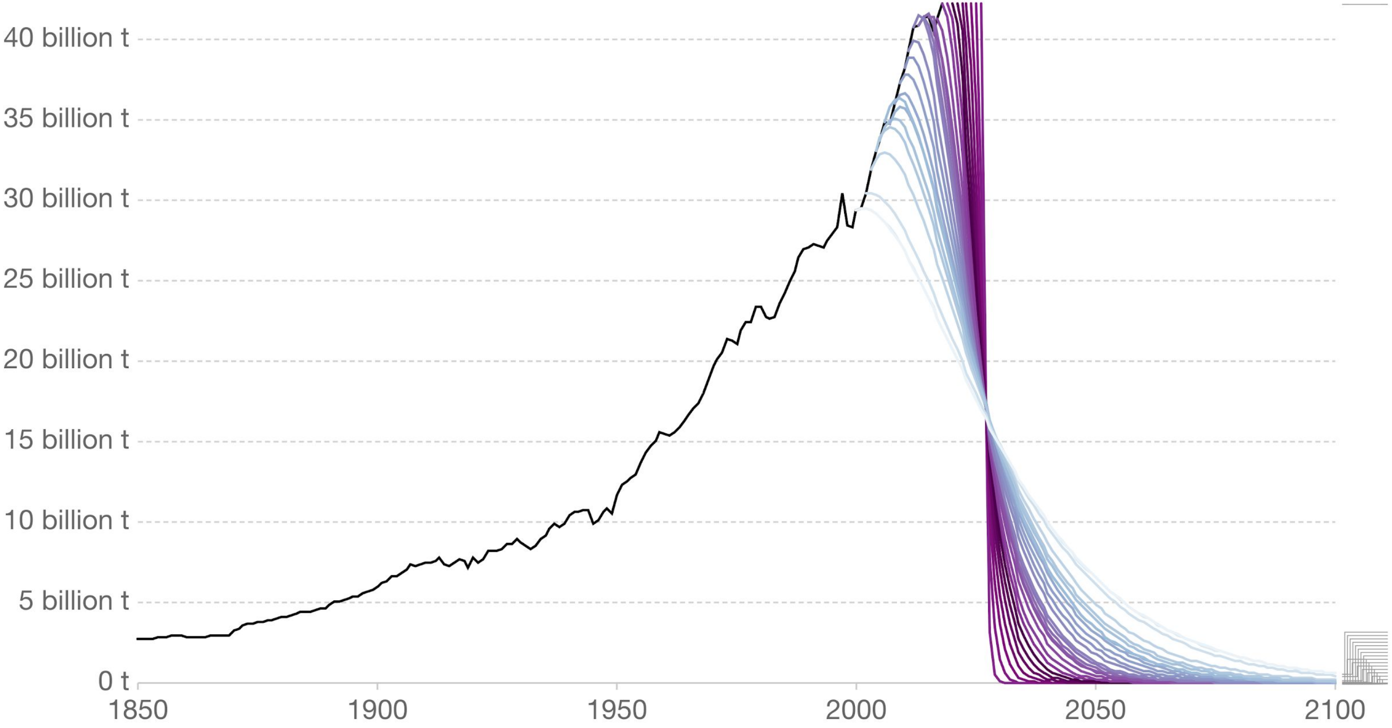
The emissions-only approach



CO_2 reductions needed to keep global temperature rise below 1.5°C

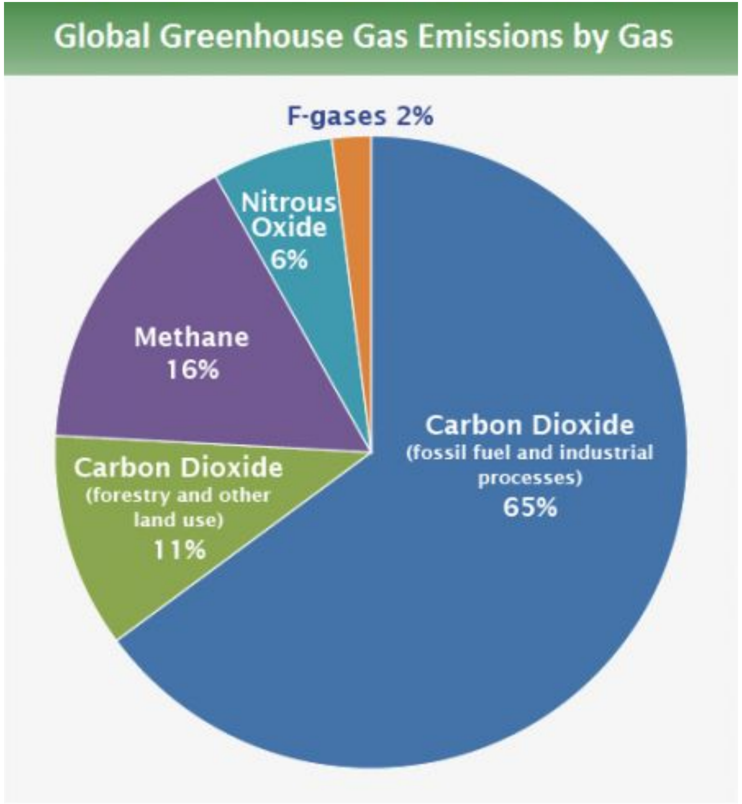
Our World in Data

Annual emissions of carbon dioxide under various mitigation scenarios to keep global average temperature rise below 1.5°C. Scenarios are based on the CO_2 reductions necessary if mitigation had started – with global emissions peaking and quickly reducing – in the given year.



Source: Robbie Andrews (2019); based on Global Carbon Project & IPPC SR15
Note: Carbon budgets are based on a >66% chance of staying below 1.5°C from the IPCC's SR15 Report.

Challenge: 25% of emissions are not carbon dioxide



Preparing for the next three decades

We need to **understand** what's behind greenhouse gas emissions to know what we need to do in order for emissions to reach **zero** in the next three decades

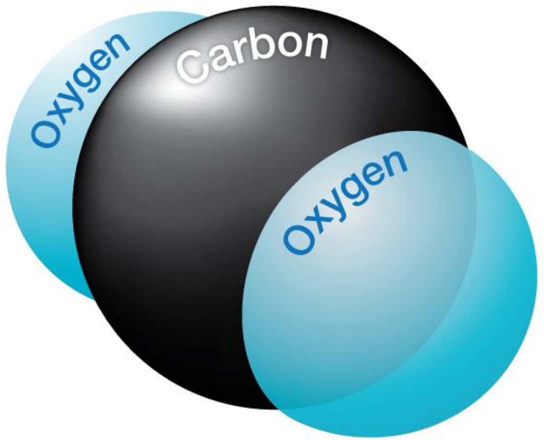
Why do humans emit so much greenhouse gas?

No one reason, there are *many diverse* sources of emissions

Broadly speaking:

Energy-related emissions are about **60-70%**

Agriculture makes up most of the remaining **30-40%**



Human energy use is substantial

For context...

Humans need only about 2000 calories of energy each day for food, which is about **100 Watts**

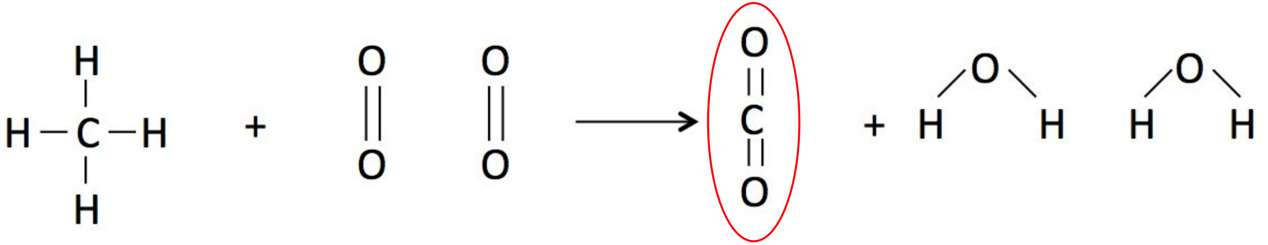
But humans actually use about **10,000 Watts** in developed countries

(100x more than needed for food)

Everything requires energy

- **Manufacturing**
  - Most materials are made with significant heat, > 1000 ºC
  - As a result, they have significant **embedded energies** - buildings are the biggest component
- **Shipping Transportation**
  - Range and capacity need to be maximized - requires substantial energy density
- **Human Transportation**
  - Air travel *requires* a significant threshold energy density
- **Heating**
  - Includes indoor space and water heating, stove flame, and dryers - all highly energy intensive
  - Electricity-provided heating is very rare, most heating is local propane or oil combustion
- **Electricity**
  - Needs to be cheap and reliable - no power outages

Releasing stored sun energy, 54% of emissions



\+ Energy (a lot)

Hydrocarbon

Methane (gas), Oil (liquid), or Coal (solid)

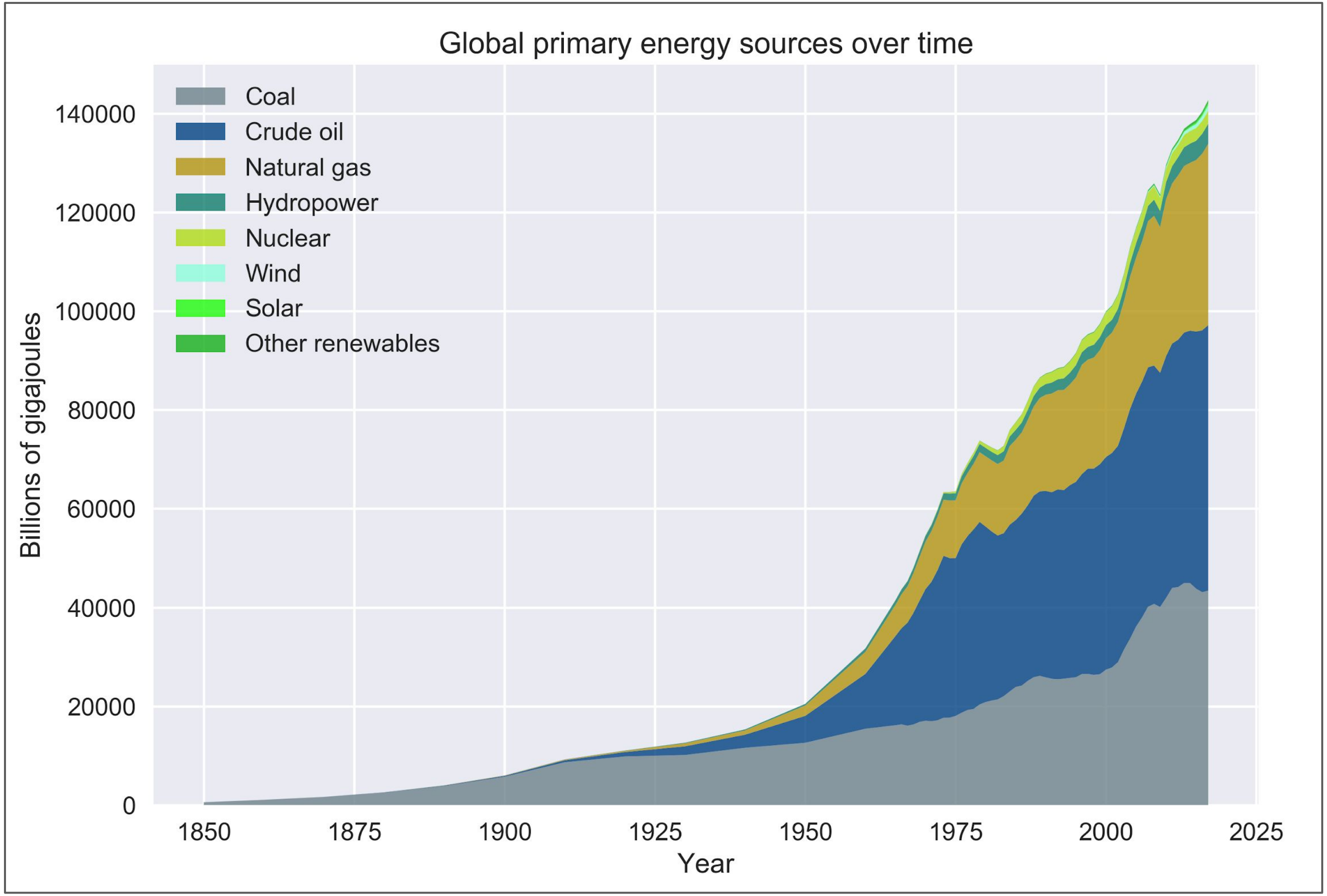
Oxygen

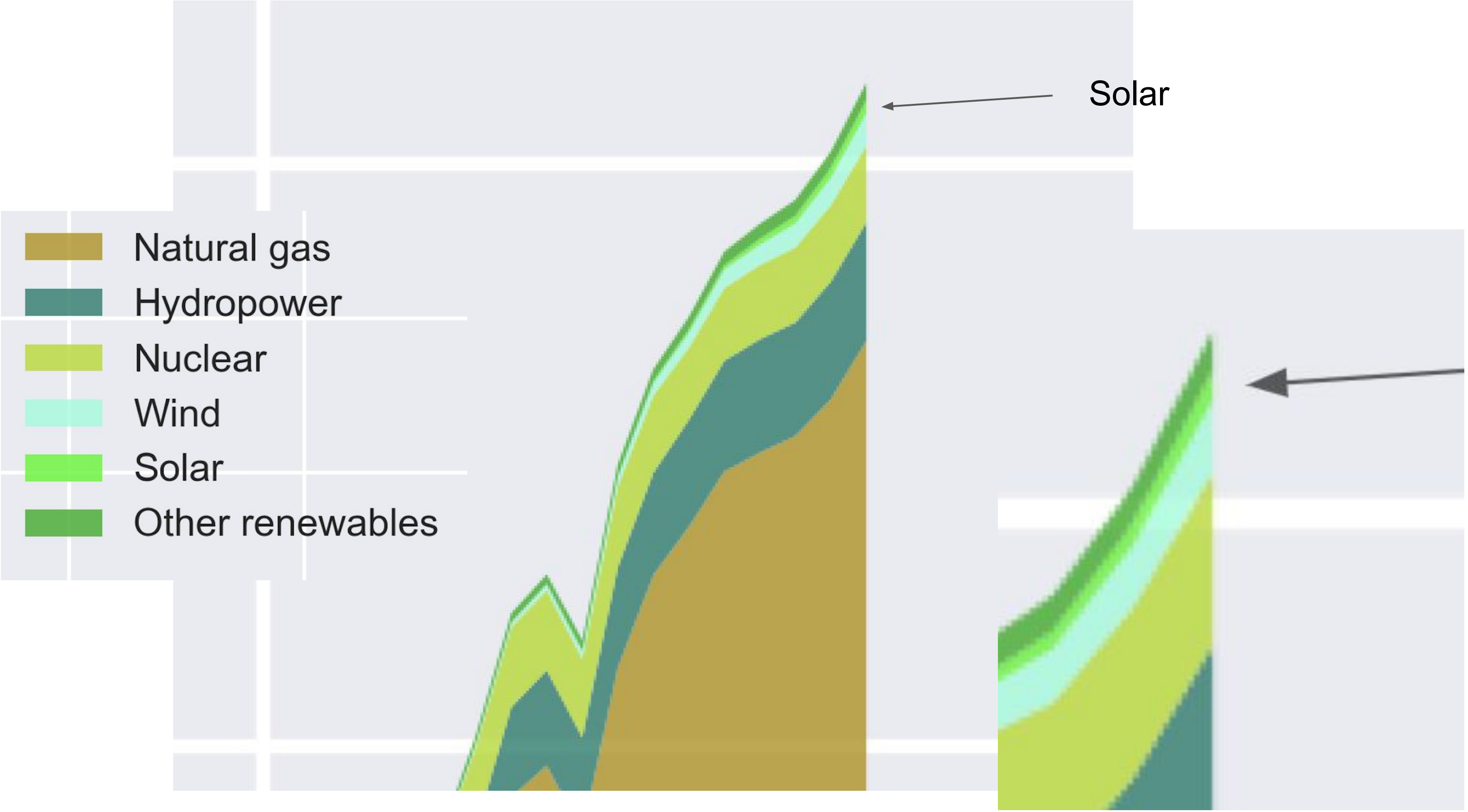
Carbon Dioxide

Steam

Heating, Electricity, Industry, Transportation, etc.

- 91% fossil fuels in 1990
- 89% fossil fuels in 2018





Solar
Natural gas
Hydropower
Nuclear
Wind
Solar
Other renewables

Why is renewable so small? The main reasons

- Most industrial energy-intensive processes are not electricity provided
  - Many of these processes intimately make use of flame-heating
- Low power density
  - Solar/Wind: 10 to 100 W/m^2
  - Coal/Oil: 1,000 to 10,000 W/m^2
  - This means large amounts of land area (3.6% of continental US covered by solar)

Why is renewable so small? The main reasons

- **Intermittent** supply, humans need reliable power
  - Weather varies (nighttime, cloudy, no wind, too much wind)
- Low density, high cost **storage**

Storage Type	**Energy Density (MJ/kg)**	**Cost ($/MJ)**
Battery	1.03	55.60
Diesel	49.5	0.06
Multiples	**~50**	**~1,000**

Very high threshold energy densities are *required* in aviation and most shipping

- Missing continent-scale **transmission** infrastructure
  - High connectivity transmission can somewhat compensate for lack of storage

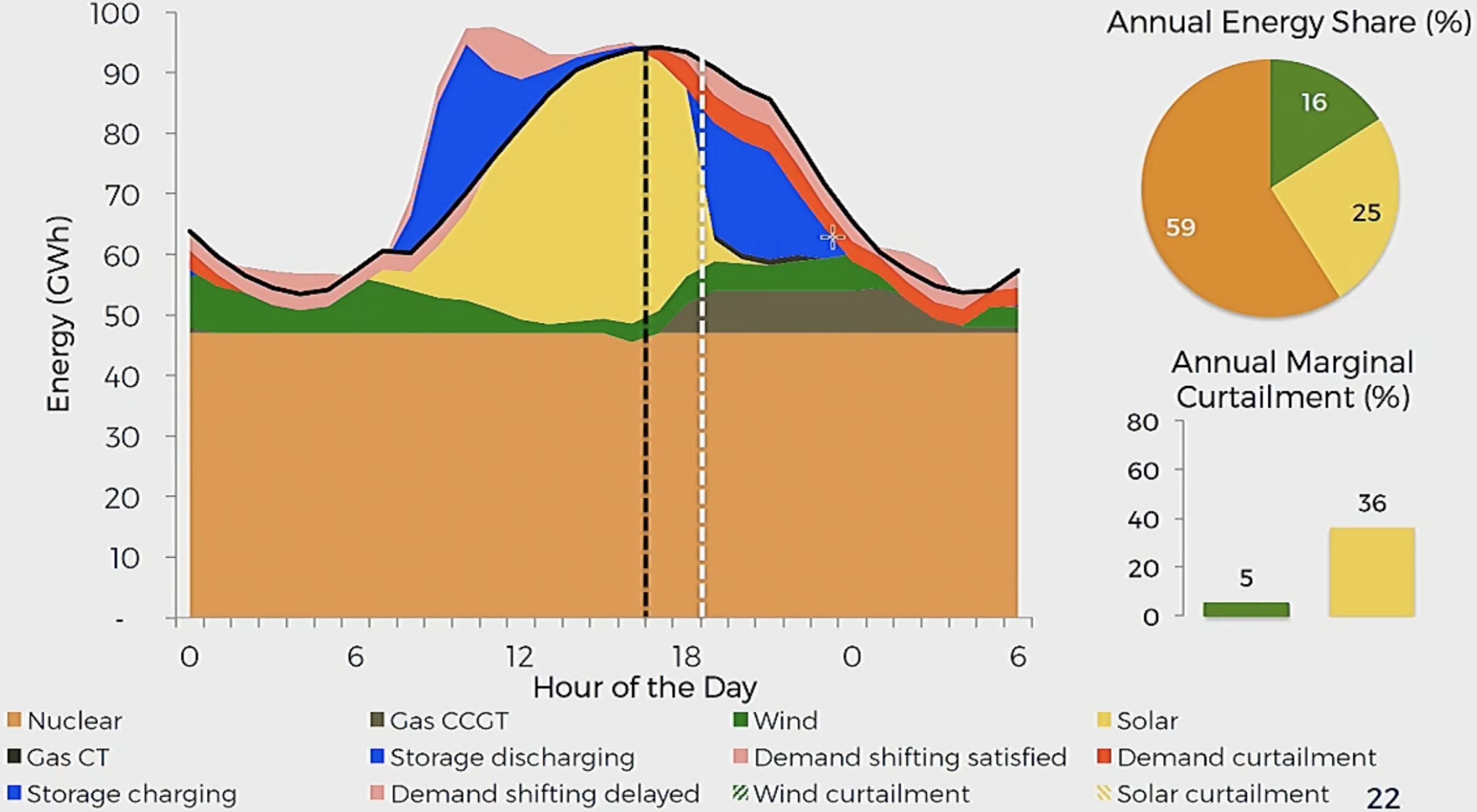
Let’s talk about electricity (~25% of emissions)

Baseload power is the **minimum** amount of electric power that needs to be supplied to the electrical grid at all times, you **cannot** dip below baseload

As a result, solar and wind **cannot** scale unless **intermittency** problem is solved

Intermittency **can** be solved through substantial research and deployment of extremely cheap seasonal storage, continent-scale transmission, and nuclear base load

The greater the nuclear component, the less miraculous storage and transmission need to be



Energy (GWh)
100
90
80
70
60
50
40
30
20
10
-
0
6
12
18
0
6
Hour of the Day
Annual Energy Share (%)
16
25
59
Annual Marginal Curtailment (%)
80
60
40
20
0
5
36
Nuclear
Gas CCGT
Wind
Solar
Gas CT
Storage discharging
Demand shifting satisfied
Demand curtailment
Storage charging
Demand shifting delayed
Wind curtailment
Solar curtailment

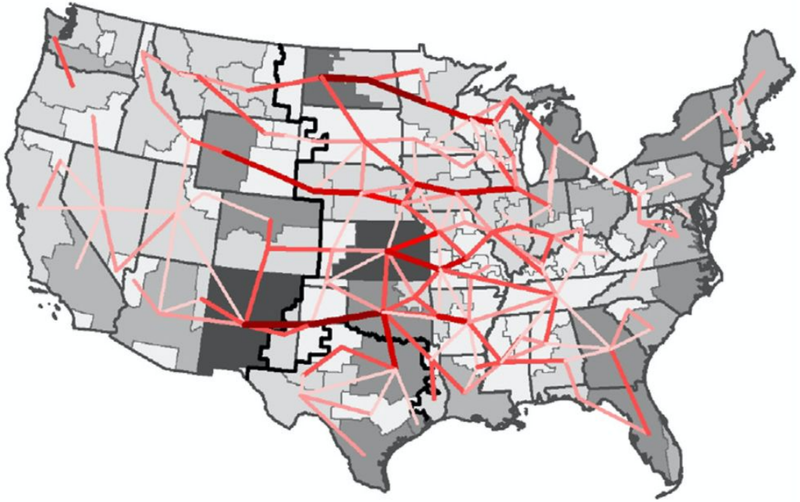
Nuclear **would** solve the electricity component, but rapid global deployment is unlikely

It is **very** difficult to solve electricity without nuclear

The problem is **not** in deployment of solar and wind, deployment is straightforward

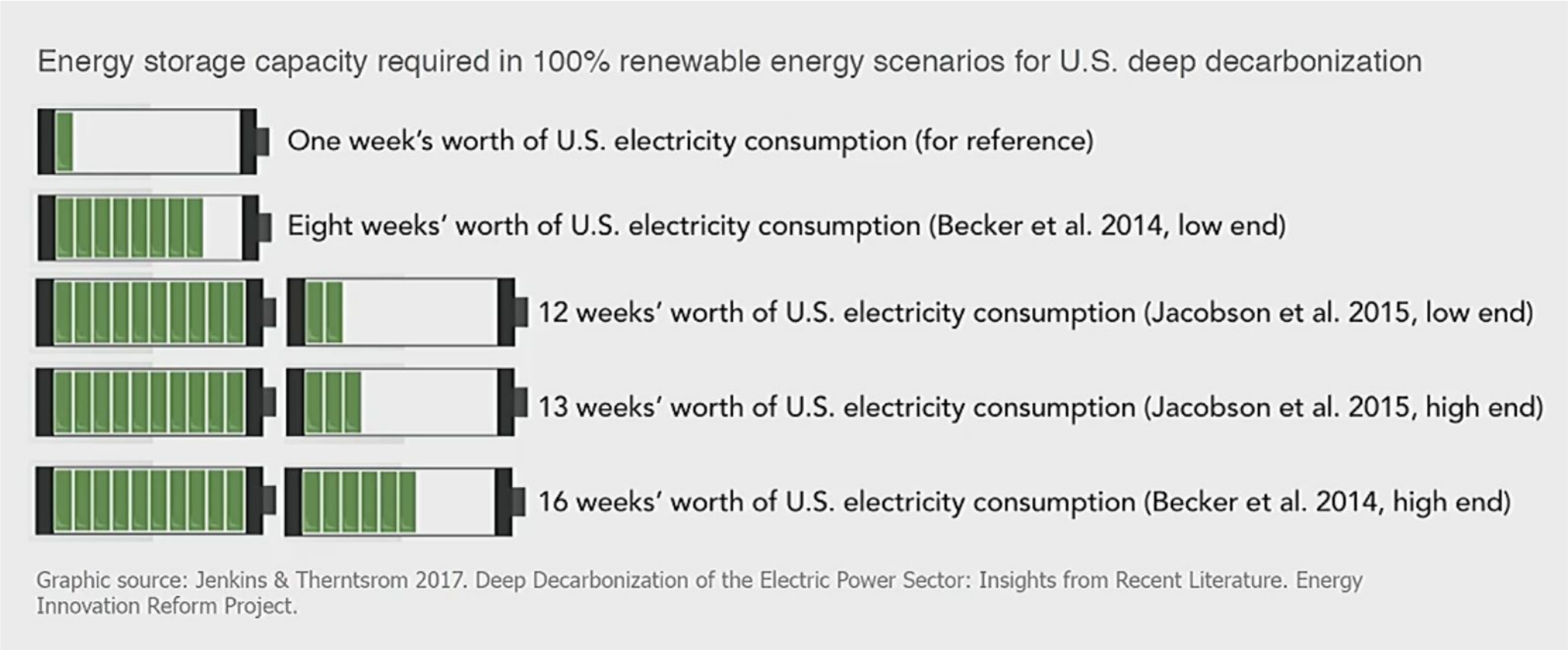
The problem is that deployment is futile unless there is **continent-scale** transmission, and large-scale storage - especially **seasonal** storage

Or, we need a *"clean firm"* source of electricity similar to nuclear - maybe combined cycle gas turbines with carbon capture and storage?



Mai et al. 2014

Seasonal storage requirements (without nuclear)



For comparison, the ten largest pumped hydro storage facilities in the United States provide enough energy storage capacity to supply average U.S. electricity needs for just *43 minutes.*

Photo of Grand Coulee Dam and John W. Keys III Pump-Generating Plant. Credit: US Bureau of Reclamation

2015 U.S. electricity consumption from EIA. Storage capacity from DOE Global Energy Storage Database.

John W. Keys III Pump-Generating Plant and Banks Lake Reservoir at Grand Coulee Dam: 25 GWh or *3 minutes and 30 seconds* of storage.

2015 U.S. electricity consumption from EIA. Storage capacity from DOE Global Energy Storage Database.

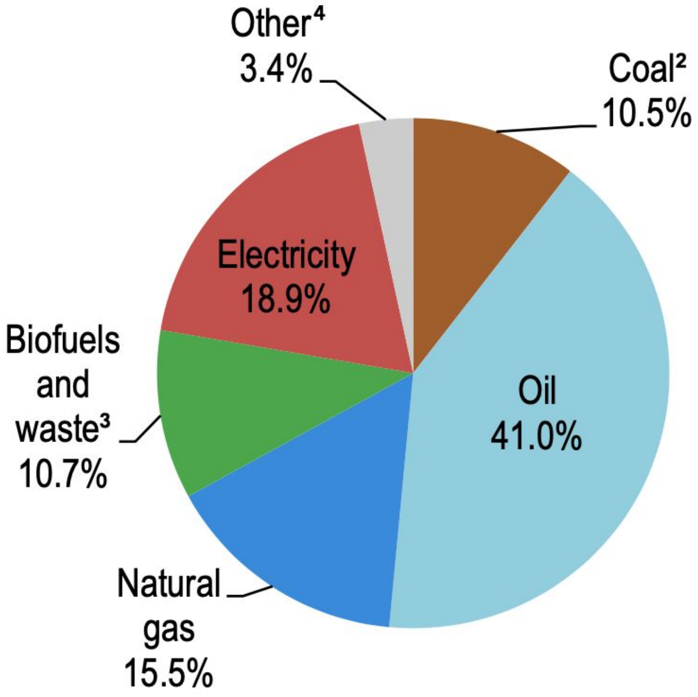
John W. Keys III Pump-Generating Plant and Banks Lake Reservoir at Grand Coulee Dam: 25 GWh or *3 minutes and 30 seconds* of storage.

Other renewables besides solar, wind, and nuclear

- **Hydro**
  - Dependent on surrounding terrain (mountainous with large bodies of water)
- **Biofuels**
  - Net emissions due to deforestation
  - Unfeasible land area requirements due to low power density (> 120% of continental US covered by corn)

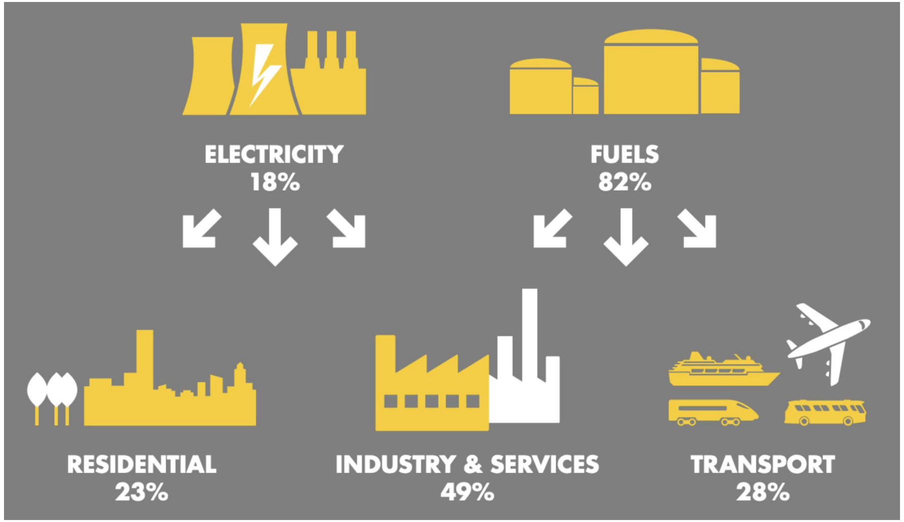
Challenge: 81% of energy is not the electricity grid

- That means 81% of global energy would not be renewable even if solar and wind were fully deployed today

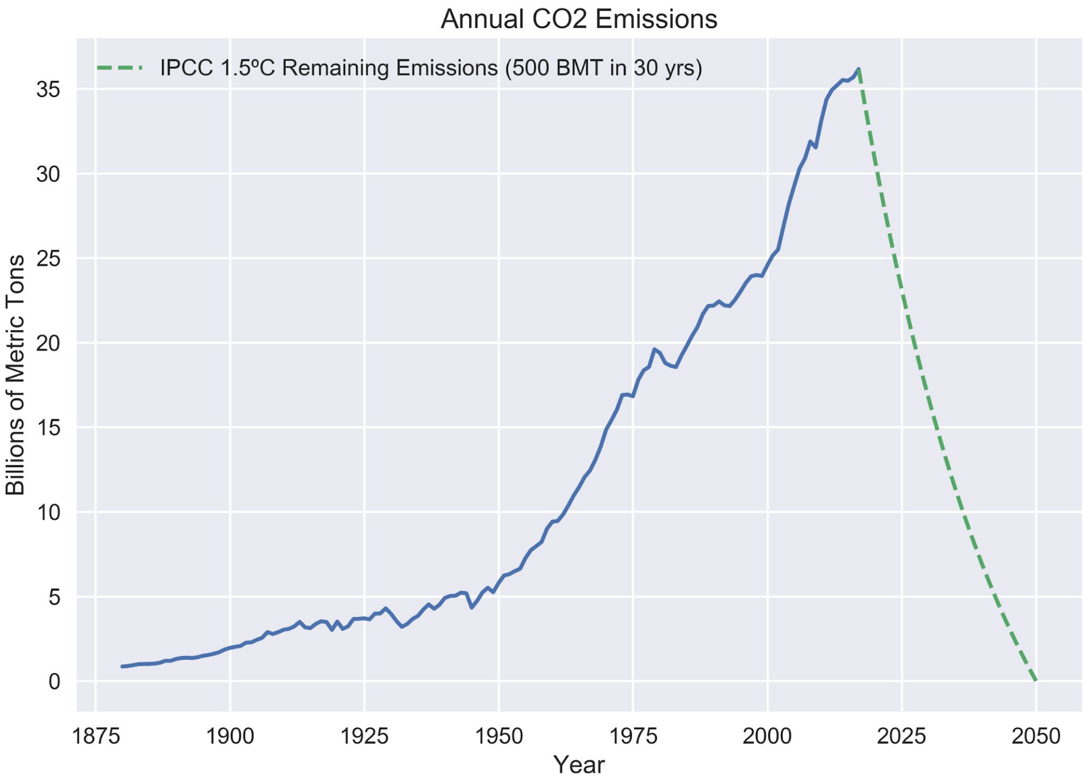


Dealing with the remaining 81%

- We need cost-effective ways to provide the remaining 81% from either:
  - Electricity grid
  - Battery storage
  - Hydrogen fuel
- Some important examples of non-electricity grid energy uses:
  - Firing cement kilns
  - Cross-ocean transport
  - Indoor heating

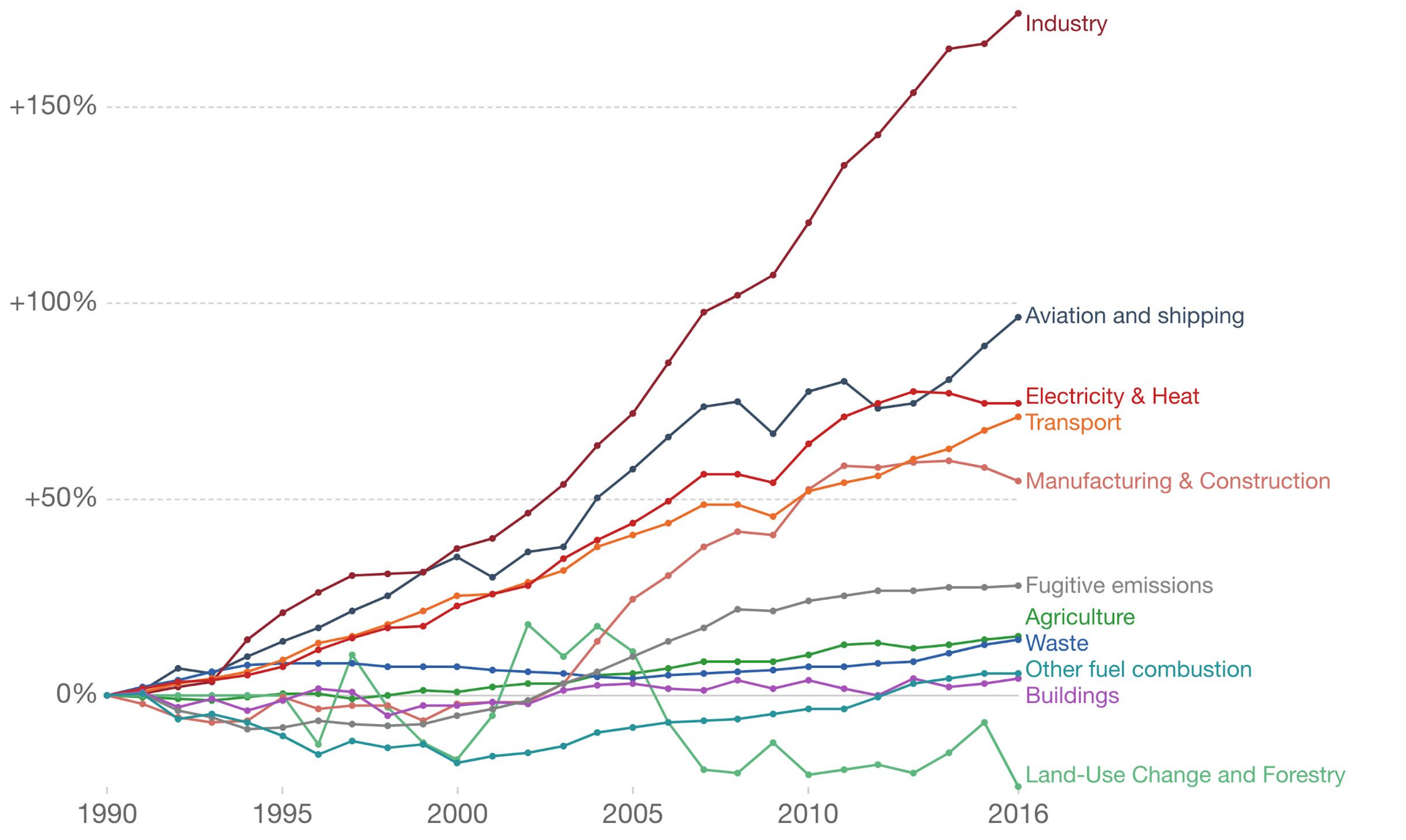


Back to emissions (need zero by 2050)



Greenhouse gas emissions by sector, World

Greenhouse gas emissions are measured in tonnes of carbon dioxide-equivalents (CO_2e).



Source: CAIT Climate Data Explorer via. Climate Watch

OurWorldInData.org/co2-and-other-greenhouse-gas-emissions • CC BY

Energy related emissions are about 70%

- **Transportation (18%)**
    - Airplanes (3.8%)
    - Container shipping (1.7%)
    - Trucking (4.5%)
    - Passenger vehicles (7.4%)
    - Rail (0.4%)
- **Manufacturing (24%)**
- **Electricity (25%)**
- **Heating (11%)**

Non-energy related emissions are about 30%

(what solar and wind cannot solve)

- **CO_2 emitted from *chemical reactions* to make basic materials** (8%)
    - Cement (calcination)
    - Steel (iron smelting, calcination)
    - Aluminum (Hall–Héroult process)
    - Plastic (steam-cracking, fugitive sources, etc.)
    - Fertilizer (Haber-Bosch process)
    - Paper (Kraft process)
    - Other Chemicals
- **Agriculture**, CH_4, N_2O, CO_2 (19%)
- **Landfills**, CH_4(1.9%)
- **Wastewater**, CH_4(1.3%)

Calcination Reaction

$$\overset{\text{calcium carbonate}}{\mathrm{CaCO_3}} \xrightarrow[\text{heat}]{} \overset{\text{calcium oxide}}{\mathrm{CaO}} + \overset{\text{carbon dioxide}}{\mathrm{CO_2}} .$$

Energy density

- The amount of energy per unit mass
- Measured in joules or kWh per kilogram
- **Very important in long distance (ocean-scale) transportation**

Container shipping (~2% of emissions)

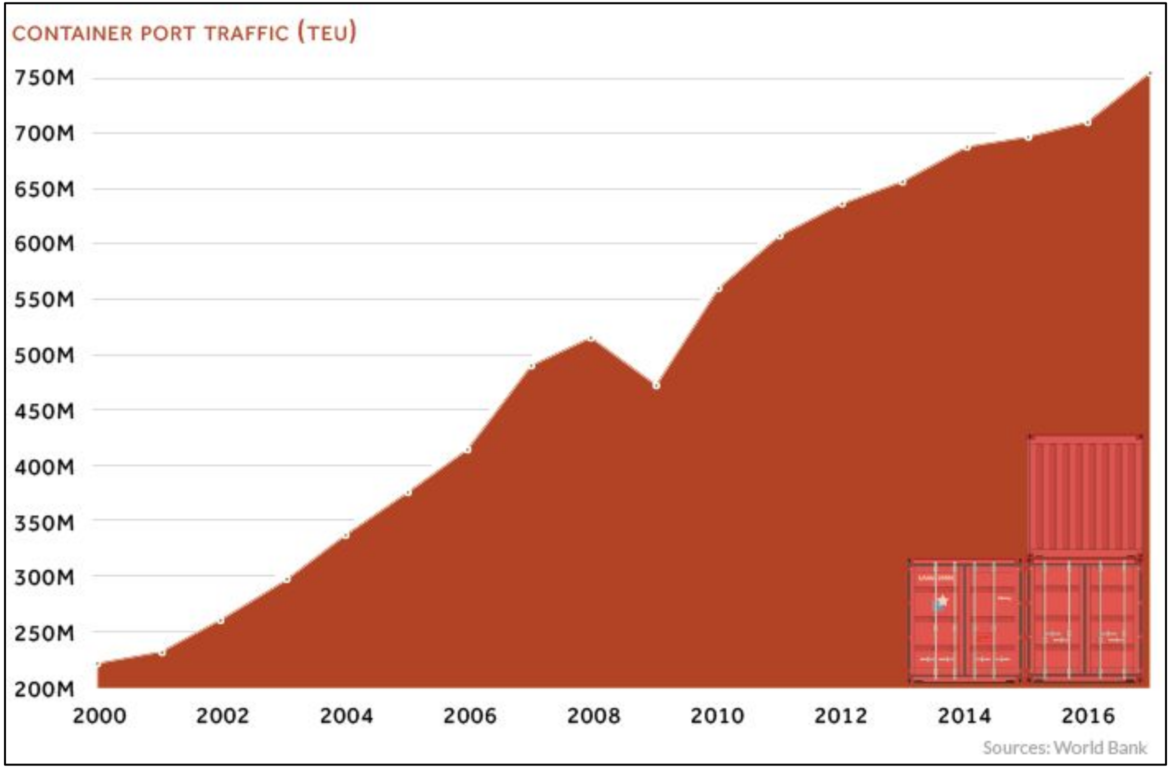
(Comparing the first battery-powered to a standard container ship)

	Capacity (containers)	**Speed (kn)**	**Power (MW)**	**Range (nm)**	**Capacity x Range**
Yara Birkeland	120	6	4	30	3,600
OOCL Hong Kong	21,413	25	80	12,000	256,956,000
Multiples	178	4.2	20	400	**~72,000**

Battery powered container ships are **5 orders of magnitude** non-economic with current battery technology

This is because of the lower **energy density** of batteries as compared to heavy fuel oil

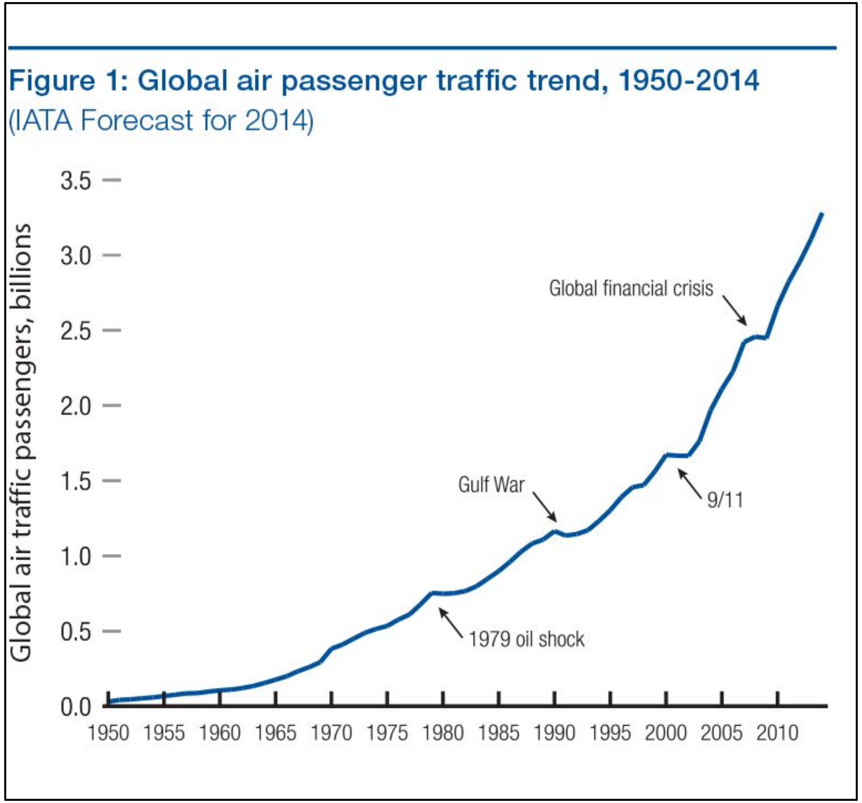
Container shipping is increasing



Airplanes (~4% of emissions)

- A commercial airplane has a maximum range of **20 minutes** on current battery technology, before it becomes too heavy to lift off
- This is < 5% of the distance between NYC and London
- Again, because kerosine is **50x** more energy dense than the best batteries
- Contrails have roughly the same warming effect (radiative forcing) as the CO_2 emitted. (Kärcher, 2018, *Nature*)

Air travel is increasing



Land use (~19% of emissions)

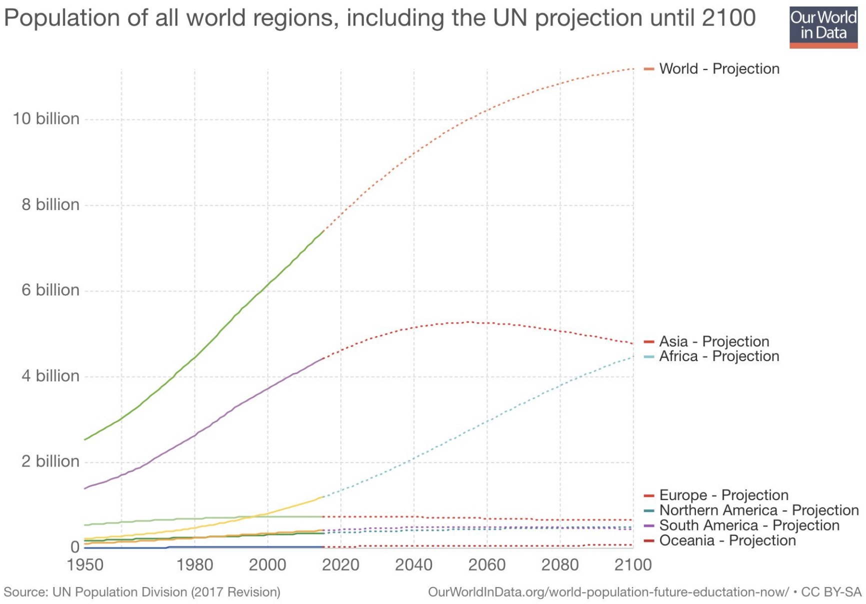
- Carbon stored in **soil** and plants is released when forest is turned to cropland or burned (8%)
- Synthetic fertilizers release NO_2 (nitrous oxide) when broken down by microbes. Natural fertilizers (manure) release some NO_2 and lots of CH_4 (methane) when decomposing (4%)

Land use (~19% of emissions)

- Grazing ruminants (cows, goats), emit CH_4 from digestive tracts (6%)
- Rice cultivation emits methane (1.3%)

Long term challenges in land-use component

- Global population to increase by 3-4 billion people
- As global GDP per capita rises, so does meat consumption
  - Meat requires ~100x more land use



Landfills (1.9%)

- Organic matter (especially wasted food) decomposes to methane in landfills

Wastewater (1.3%)

- Similarly, organic waste from animals, plants, and humans emits NO_2 and CH_4 when it decomposes

The story behind cement/concrete (~4% of emissions)

Limestone (fossil)

Where it begins

Limestone quarry

Chemical reactions to make cement

First, combust **limestone** to remove carbon and get calcium oxide (calcination)

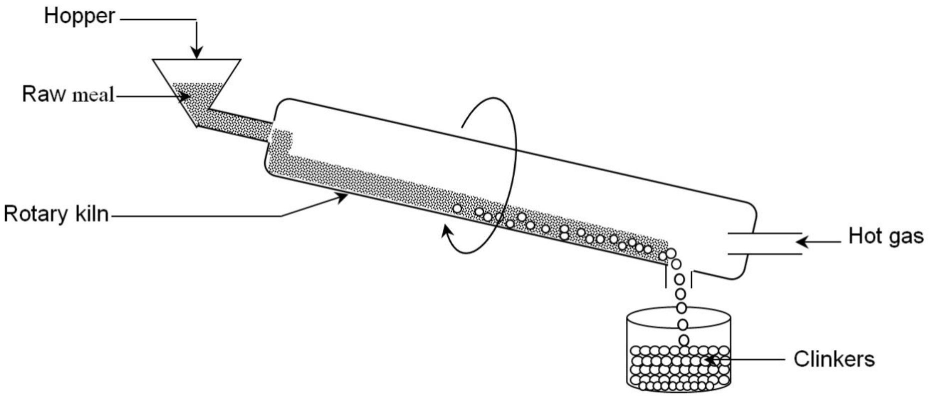
$$\underset{\text{(Limestone)}}{\overset{\text{calcium carbonate}}{CaCO_3}} \xrightarrow[\text{heat}]{} \overset{\text{calcium oxide}}{CaO} + \overset{\text{carbon dioxide}}{CO_2}.$$

Then, react calcium oxide with other chemicals to make cement

$$\underset{\text{Calcium Oxide}}{4CaO} + \underset{\text{Aluminium oxide}}{Al_2O_3} + \underset{\text{Ferric oxide}}{Fe_2O_3} \longrightarrow \underset{\text{Cement}}{4CaO.Al_2O_3.Fe_2O_3}$$

Chemical reactions occurs in cement kiln

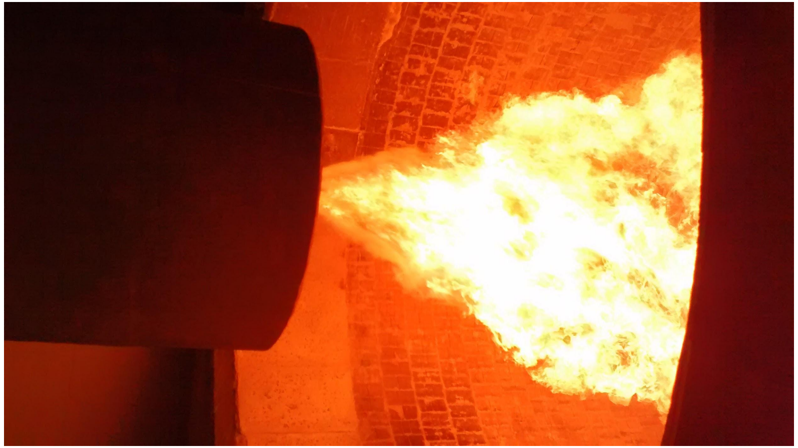
- Heated from 70 ºC to 1,500 ºC
- Kiln is spun to form klinkers



Manufacture of cement

Kiln is fired with coal

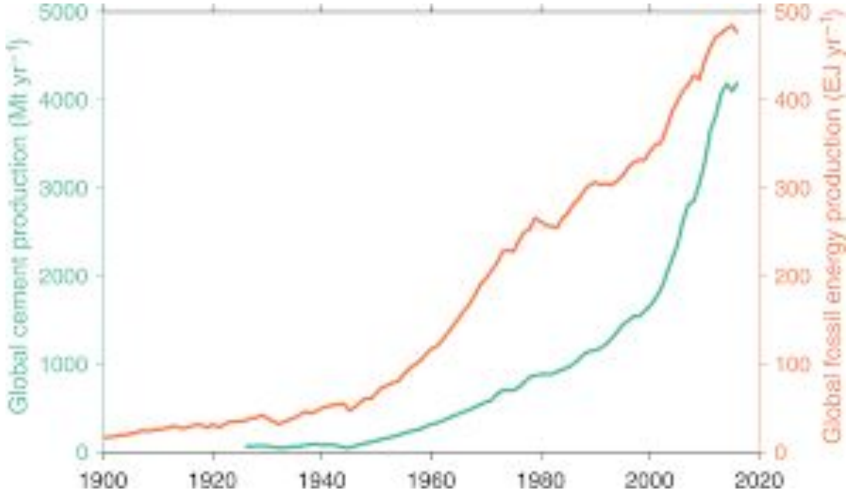
- Bright hot flame needed
- Coal produces very bright flame at 2050 ºC



Cement kiln

Concrete is important, and growing

- Good building material
  - Rust-resistant
  - Rot-proof
  - Non-flammable
- Buildings
- Bridges
- Roads
- Tunnels
- Dams
- Pipes



(Started with limestone)

Cement

Concrete

Add sand, water, and gravel to make concrete

The story behind steel (~7% of emissions)

Iron ore (iron oxide)

Coal

Where it begins

Iron ore mine

Coal mine

Diesel trucks, onsite electricity generation, seam gas (methane)

Turn coal into coke

Coal gets baked at 1,100 °C to become **Coke** (higher carbon content)

Coke Oven

Coke

Chemical reactions to make steel

First, combust **coke** to make carbon monoxide.

(The fossil carbon is used as a <u>reducing agent</u> and as an <u>energy source - fuel</u>)

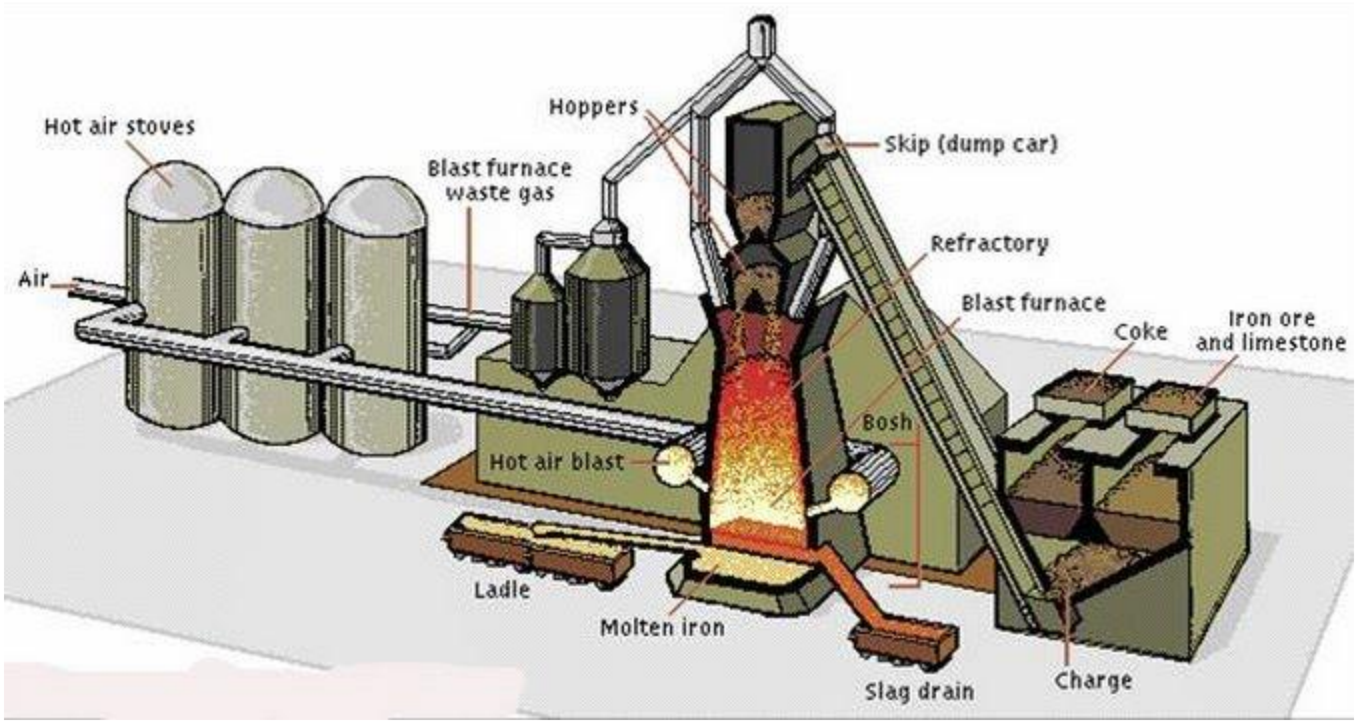
$$2C(s) + O_2(g) \rightarrow 2CO(g)$$

Coke Oxygen Carbon monoxide

Then, use the carbon monoxide to remove the oxygen (smelting)

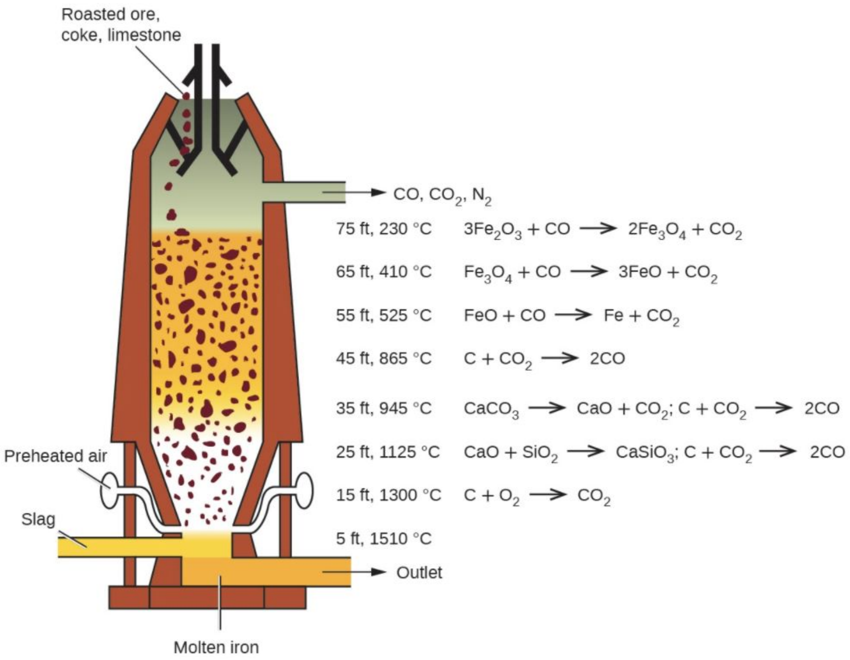
$$FeO_{(s)} + CO_{(g)} \rightarrow Fe_{(s)} + CO_{2\,(g)}$$

Iron ore (iron oxide) Carbon monoxide **Steel** Carbon Dioxide


Hot air stoves
Hoppers
Blast furnace
waste gas
Skip (dump car)
Refractory
Air
Blast furnace
Coke
Iron ore
and limestone
Bosh
Hot air blast
Ladle
Molten iron
Slag drain
Charge

Smelting reaction occurs in blast furnace

- Heated to >1,800 ºC
- Limestone is burned to remove other impurities (chemical flux)
- The brittle pig iron is then decarbonized to make steel (releases the remaining carbon as CO_2)



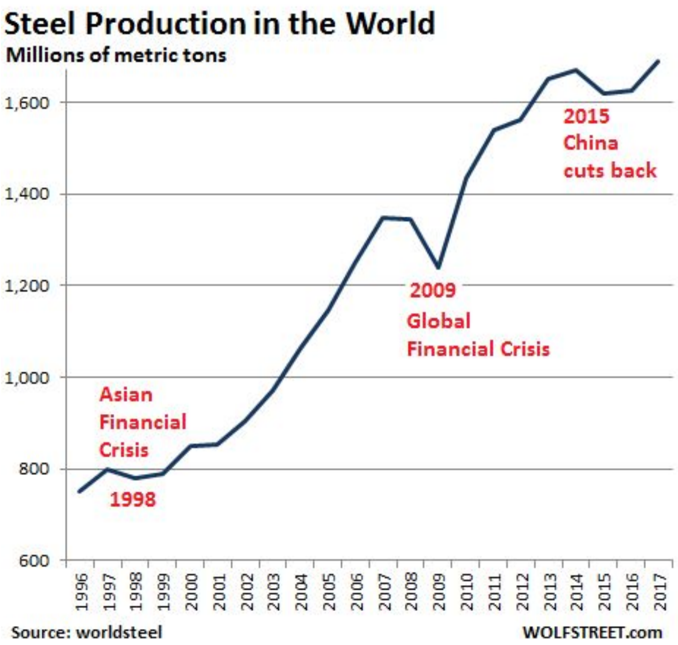
(Started with iron ore and coal)

- About 1.9 tons of CO_2 for every ton of steel produced.

Steel is fundamental, and growing

Almost everything is made of or made by steel

- Transportation
  - Cars, trucks, planes, trains
- Transportation infrastructure
  - Bridges, railways, tunnels
- Buildings
  - Beams, reinforced concrete
  - Building stock to double by 2060
- Saws
- Polishing
- Textile machinery



Aluminum (~0.5% of emissions)

Aluminum ore (bauxite)

Hall–Héroult process (aluminum smelting)

- Oxygen is removed from the aluminum ore through an electrolytic reaction
- As with steel, the fossil coke is used as the reducing agent
- Substantial electricity required (often located next to power plants)

$$2\ Al_2O_3 + 3\ C \rightarrow 4\ Al + 3\ CO_2$$

(Started with aluminum ore and coal)

- About 12.7 tons of CO_2 for every ton of aluminum produced.

The story behind plastic (~1% of emissions)

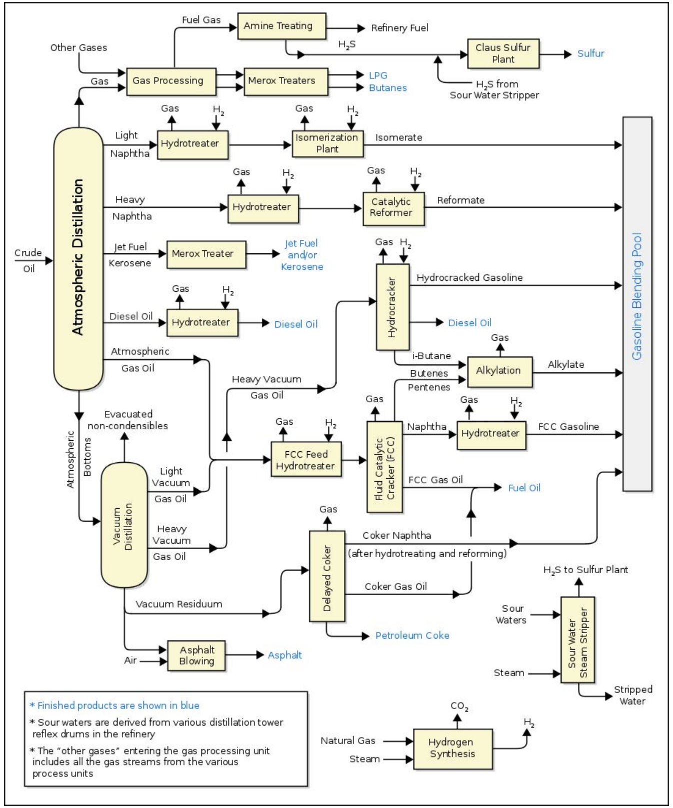
- Plastic is made from **crude oil**
- Carbon dioxide is emitted from steam-cracking, in which saturated fossil hydrocarbons are converted into useable petrochemicals
- The frequent leakage of methane from oil and natural gas pipelines is called ‘fugitive emissions’

Oil refineries (~3% of emissions)

- Oil comes out of the ground as crude oil

Oil is separated at 600ºC to make:

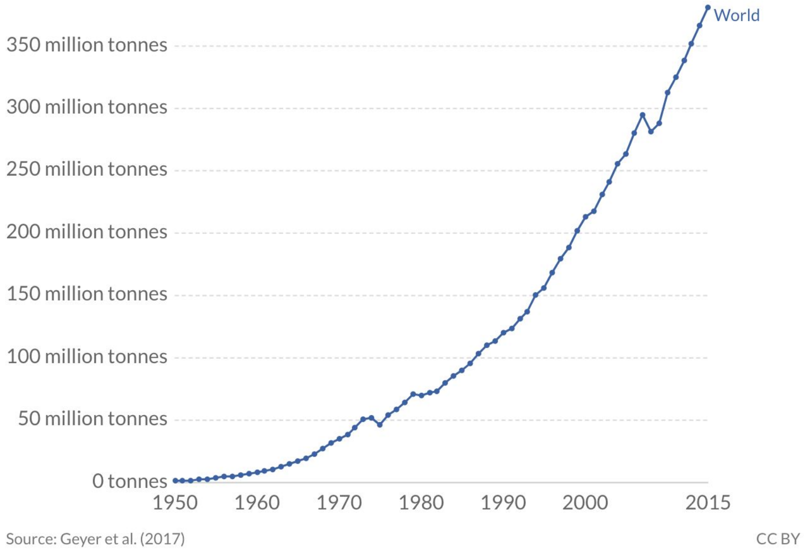
- Plastic
- Asphalt
- Kerosine (airplanes)
- Home heating oil (diesel)
- Gasoline
- Industrial lubricant



Oil refinery

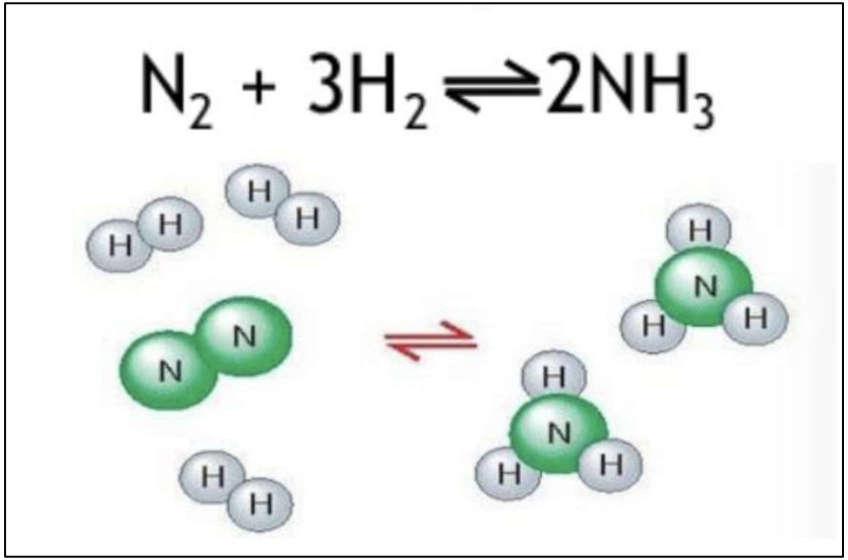
Plastic is important, and growing

- Light malleable material
  - Important in shipping
  - Cars would be 3x heavier w/out plastic
- Plastic parts are ubiquitous
  - Appliances
  - Computers
  - Machines
  - Furniture
- Sterile medical equipment
- Consumer products
  - Salient, but small component



Fertilizer production (~1% of emissions)

- Nitrogen is needed to live
- There's only enough nitrogen in the human and domestic animal nitrogen cycle to feed ~45% of the world population
- So, remaining nitrogen is obtained from atmospheric N_2

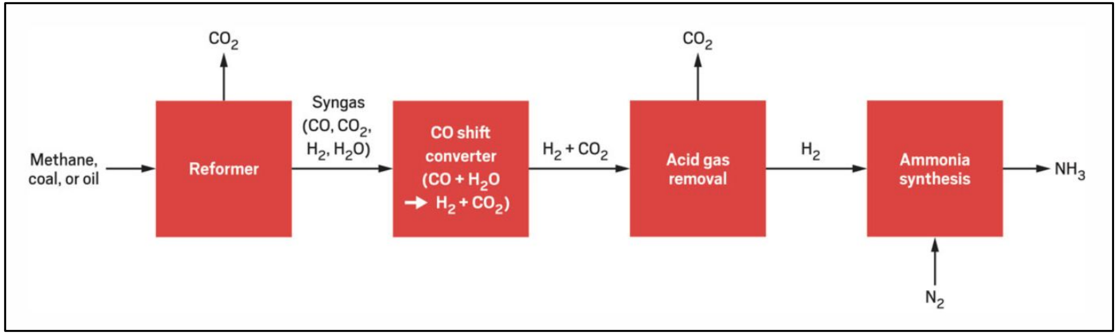


Haber-Bosch process to make ammonia (NH_3)

- The hydrogen (H_2) comes from a fossil carbon feedstock
  - Usually natural gas (CH_4)
  - Sometimes oil or coal
- Very energy intensive process
  - Triple bond in N_2 needs to be broken
  - 500 ºC
  - 200x atmospheric pressure

$$2\,CH_{4(g)} + O_{2(g)} \rightarrow 2\,CO_{(g)} + 4\,H_{2(g)}$$

$$CO_{(g)} + H_2O(g) \rightarrow CO_{2(g)} + H_{2(g)}$$



Haber-Bosch factory

Nearly half the global population could not live without the Haber-Bosch process

"Four pillars of modern civilization"
- Vaclav Smil

Pillar of Civilization	**Energy Intensity (GJ/metric ton)**	**Output (Mt/y)**	**Dominant Energies**
Steel	20	1,100	Coal (coke), natural gas
Concrete	4	4,200	Coal, petcoke, oil, natural gas
Ammonia Fertilizer	30	180	Natural gas
Plastic	100	300	Natural gas, crude oil

How might wind turbines not be zero-carbon?

Wind turbines are **not yet** zero-carbon

(Carbon emitting chemical reactions and embedded fossil fuel energies)

- **Steel** tower and transmission lines
- **Concrete** foundation
- **Plastic** blades
- **Oil** lubricants
- **Diesel** powered construction machinery
- **Glass**-fiber laminations
    - Made in > 1,700ºC natural gas furnaces

Forecasted wind turbines by 2030 would need 0.8 billion metric tons of coal. Turbines have a 20-25 year lifespan.

Emissions with no alternative technology deployable

● Airplanes (1.6%)	1903
● Cement (3.8%)	1890
● Steel (5.2%)	1709
● Plastic (1%)	1907
● Haber-Bosch (1%)	1909
● Container shipping (2%)	1956
● Fertilizer use (6%)	1903

Total: ~20%

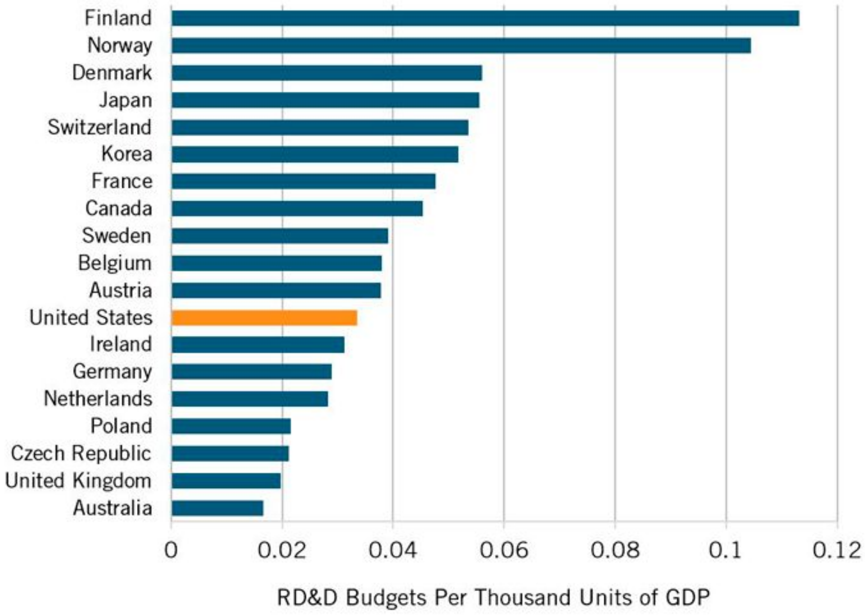
(Notice that these are largely turn of the century inventions/discoveries)

Policies that would help, but not guarantee zero

- Fund research and development (R&D)
  - Triple or quadruple current budgets
  - Hydrogen fuel?
  - Generation IV nuclear?
- Revenue neutral carbon price
  - Send currently missing price signal
  - Applicable to wealthy countries

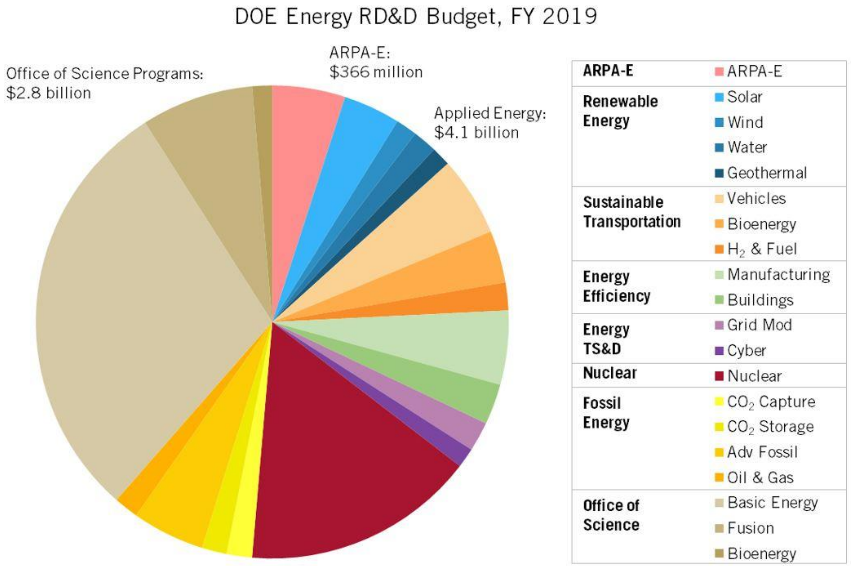
Energy R&D budgets are miniscule now

- Developed countries are funding energy R&D at about 0.02% - 0.06% of GDP
- With an income of $30,000 a year, you would end up paying about $9 for energy R&D



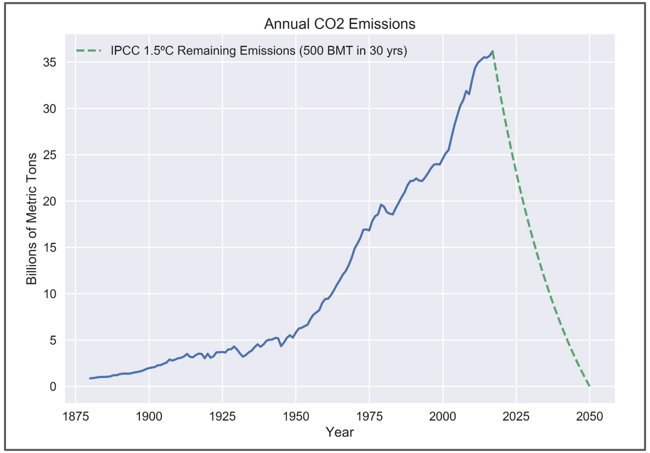
R&D is needed to create cost-effective and non-emitting alternatives

- R&D can have a long lead time, so we need to increase funding as early as possible
- Funding needs to *begin* for eliminating emissions from industrial process (chemical reactions) and agricultural sources



Is the emissions-only approach realistic?

Here's what would need to happen in 30 years:



1. Rapid invention of new technologies
    a. Reinvention of air travel, shipping, dairy and meat, landfilling, fertilizer, etc.
    b. New chemical pathways
        i. Steel, cement, ammonia fertilizer, plastic, and others
    c. New batteries
        i. Multiple order of magnitude improvements in cost and density
    d. Electrification
        i. All residential, industrial, and transportation processes
2. Rapid global adoption of new technologies
    a. Including the adoption of non-emitting transportation and electricity across 194 countries
3. New technologies cannot be vastly more expensive as they must be globally accessible

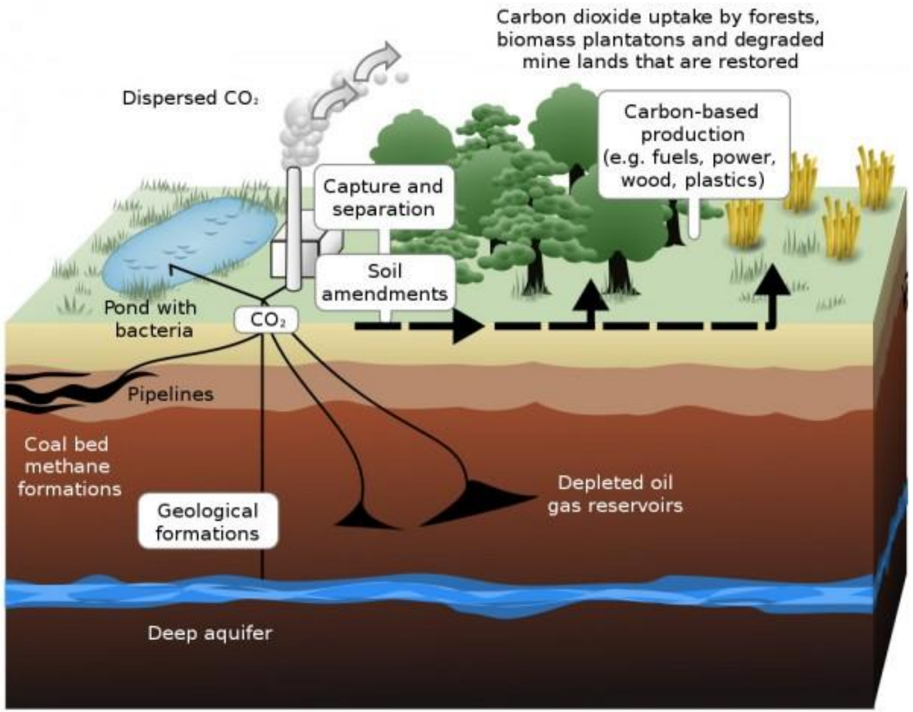
Atmospheric carbon dioxide removal?

- CO_2 gas would need to be captured from the air and buried deep underground - against the Earth's gradient (solid -> liquid -> gas)
- The feasibility of no leakage over hundreds of years is highly uncertain

Large scale physical and economic challenges

Current estimates of $200-1000 per ton mean that recapturing 2018's CO_2 emissions would:

- Cost about as much as the entire GDP of the E.U.
- Require an industry eight times larger than the global oil industry (in terms of the amount of mass needed to be moved, except in the reverse direction - down)



Regardless, carbon dioxide removal might help

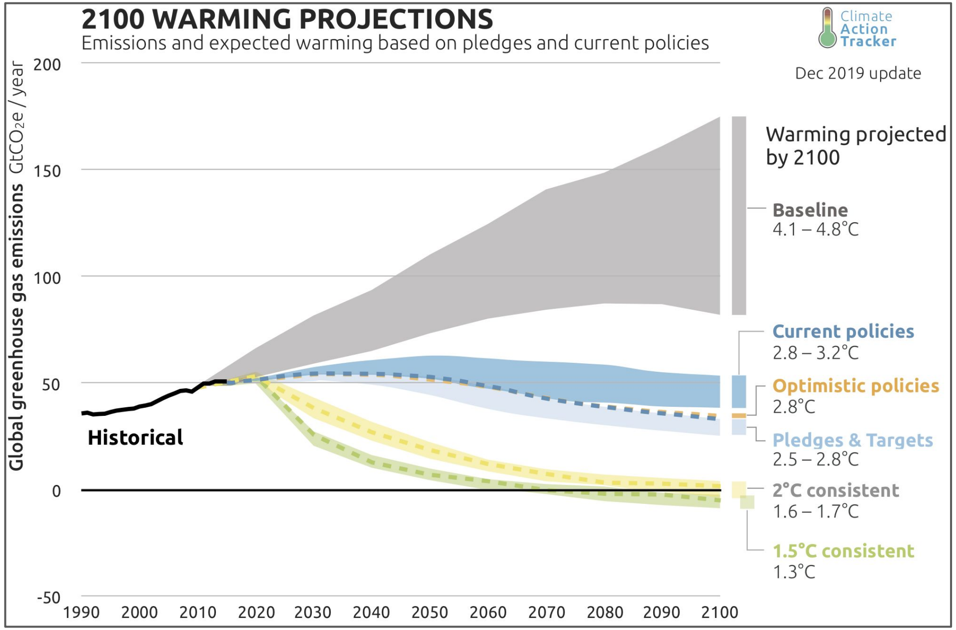
- Because of the basic physical constraints, carbon dioxide removal would likely not be practical on the scale of many billions of tons per year
- However, it could be useful if:
  - Emissions are already very close to zero
  - Innovations bring down the cost per ton of removal

What if it's 2050 and we haven't reached zero?

Do we allow the temperature rise to continue past 1.5 ºC?

At what temperature-rise do we consider approaches other than the emissions-only one?

2 ºC, 3 ºC?

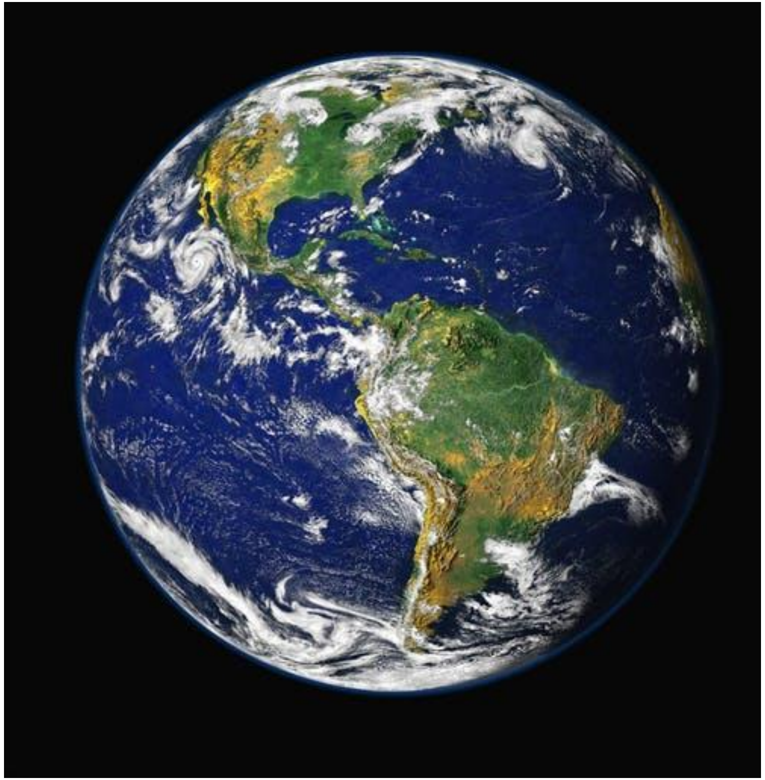


A potentially useful analogy

The biosphere is like a human body

If a human body has a life threatening fever, doctors wouldn't only focus on curing the root illness

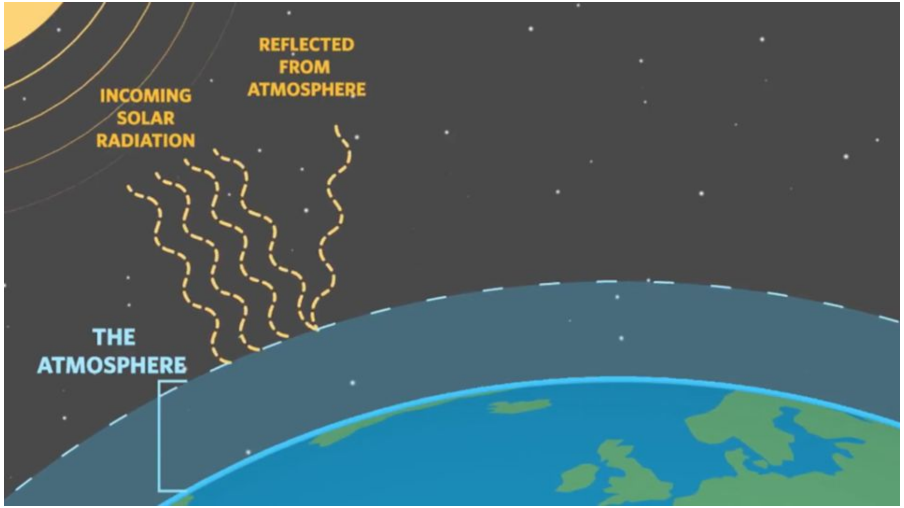
They'd work on solving the root cause and in the meantime, reduce the fever



How would we reduce Earth's fever?

Earth's temperature is rising because the Earth is **absorbing** more light from the Sun than it is **reflecting**

Thus, if we hope to reduce Earth's fever, we need the Earth to reflect more sunlight

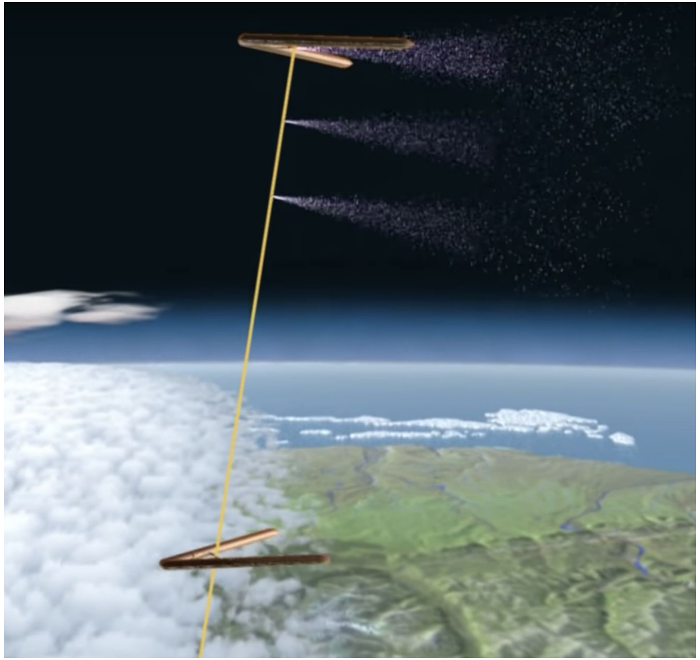


We do this all the time
(it’s called solar radiation management)

On a hot summer day, people prevent their cars from heating up by reflecting sunlight (solar radiation)

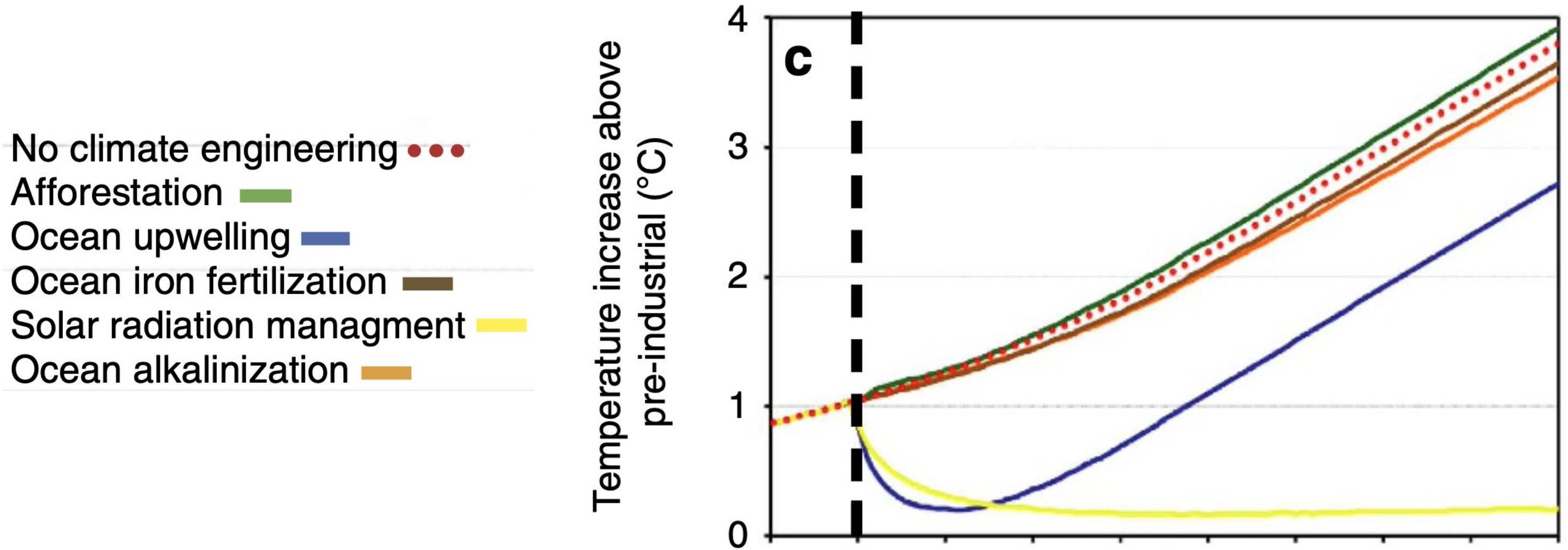
SRM has been deeply studied, there are many tools

- Stratoshield " hose to the sky". One garden hose at the north pole, one at the south pole, both releasing sulfur
  - This has the advantage of having already occurred (1991 Mt. Pinatubo)
- 10,000 buoys in the ocean that kick up saltwater around which clouds form
- Lengthen coal plant chimneys
  - Doesn’t change what’s added to the atmosphere



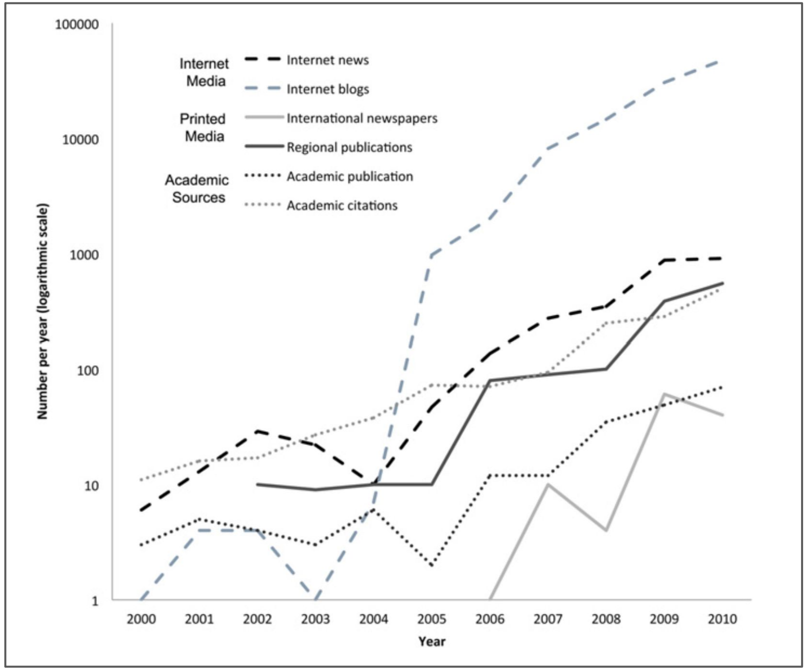
Intellectual Ventures, 2009

Paper in *Nature* about geo-engineering methods



Keller et al. 2014

SRM has been getting some attention



Mercer et al. 2011

What does the public think of SRM?

- 57% are 'not at all familiar'

Upon reading about it:

- 67% somewhat or strongly support **use**
- 81% somewhat or strongly support **research**

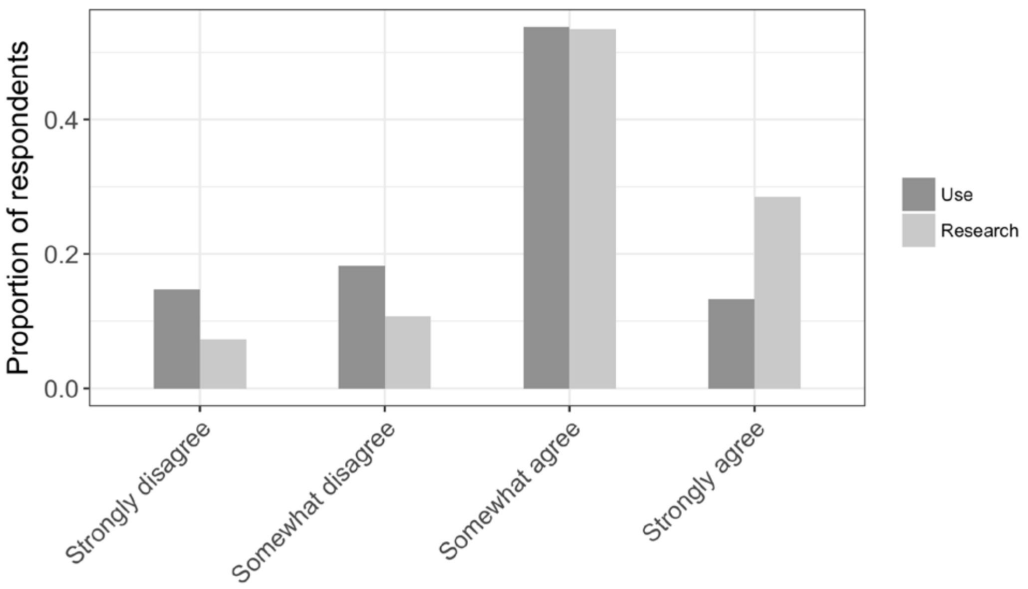
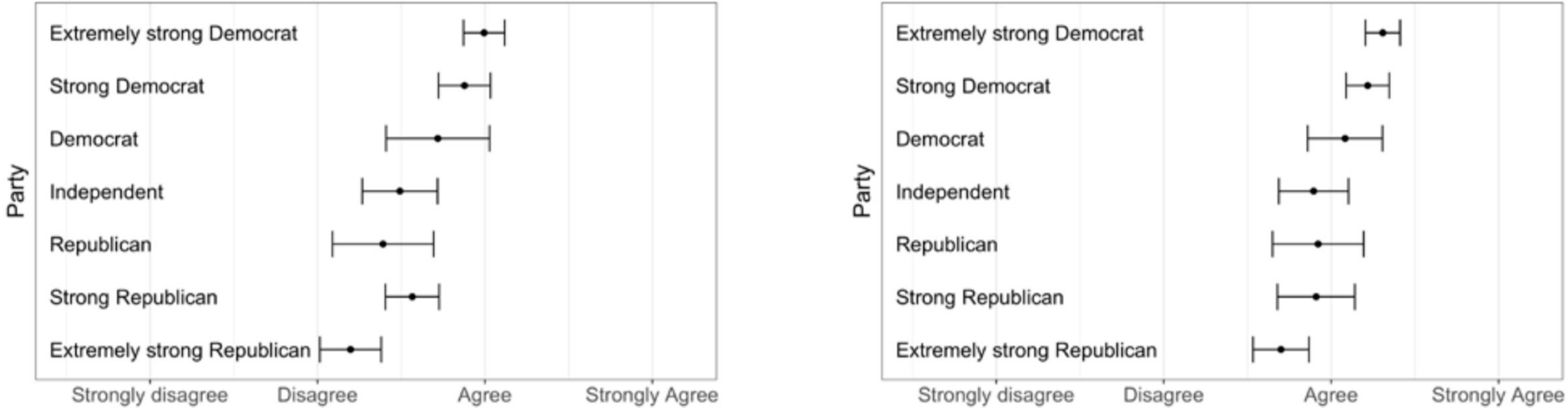


Figure 2. Distribution of support for use of and research into solar geoengineering.

Mahajan et al. 2018

Support for SRM is higher among young and left-leaning



(a) Use (b) Research

Figure 3: Support for (a) use and (b) research of solar geoengineering by party

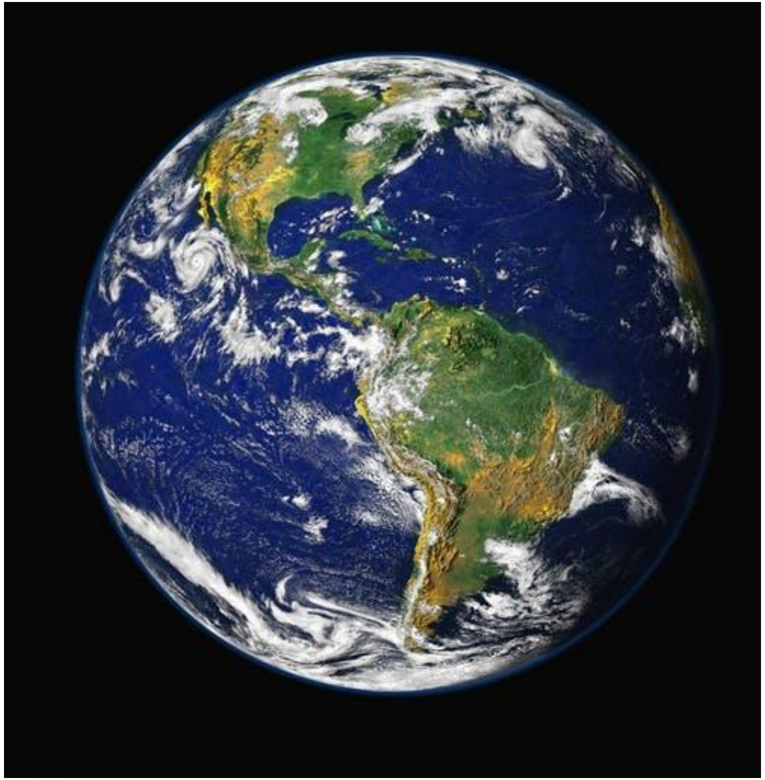
Mahajan et al. 2018

SRM is fast, cheap, and **imperfect**

- SRM does not address the problem of ocean acidification
- But perhaps ocean acidification can be solved directly on its own?
  - This might be important research to fund

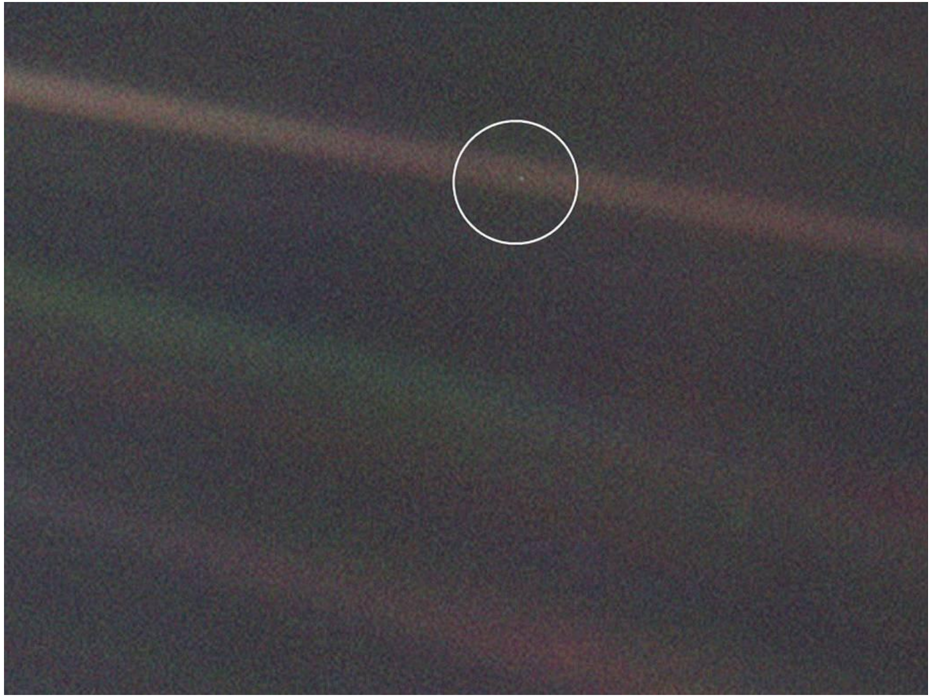
SRM in the context of climate change

- SRM is **not** a replacement for decarbonization. However, it **prevents** the ecological and human destruction that results from exceeding 1.5 ºC
- Can SRM and rapid emissions reductions be ethically combined to minimize environmental damage?
- If 1.5 ºC is unacceptable to us and zero emissions is not achieved by 2050, what other choice would we have?



“The pale blue dot, the only home we've ever known”

- Carl Sagan



Thank you

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