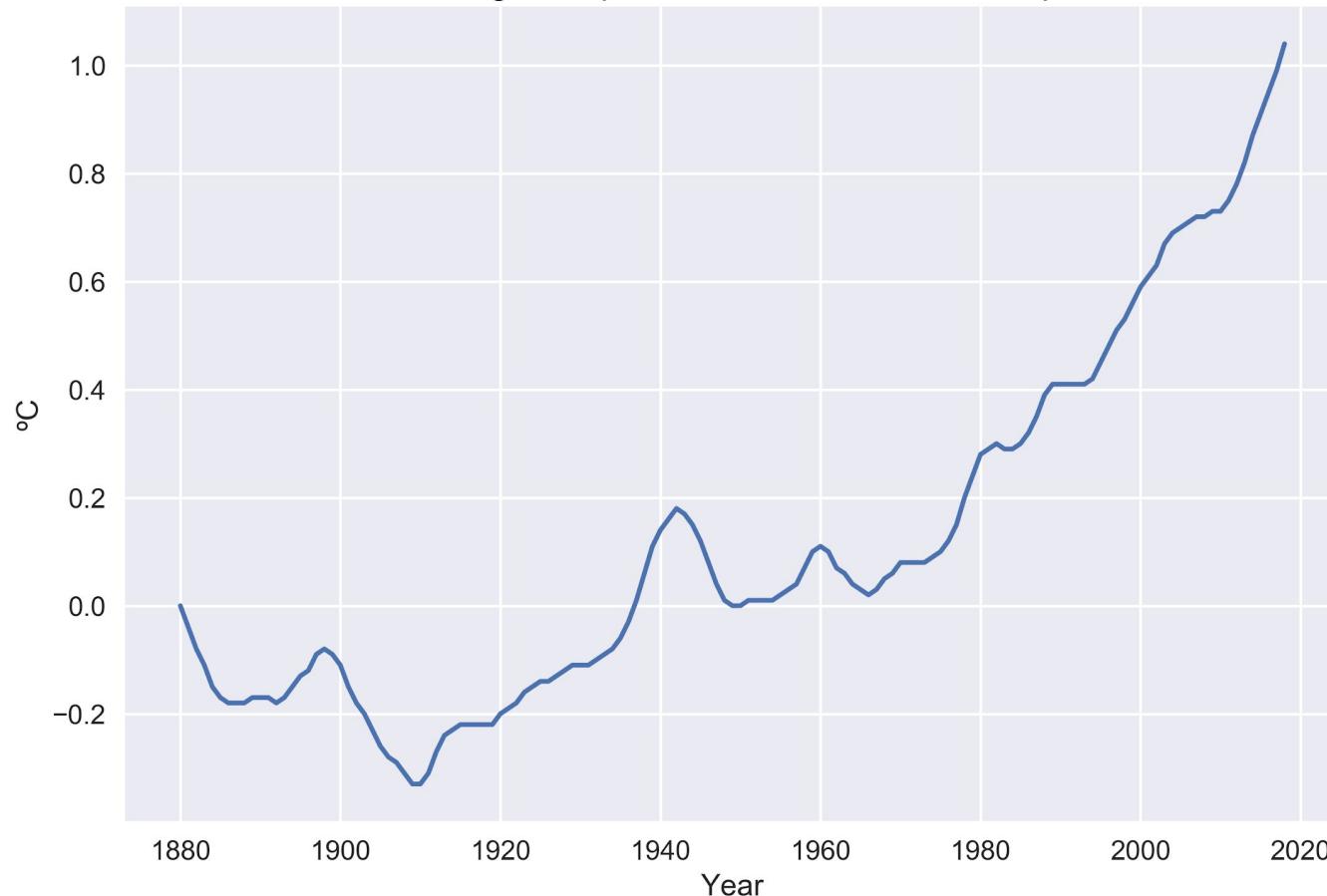


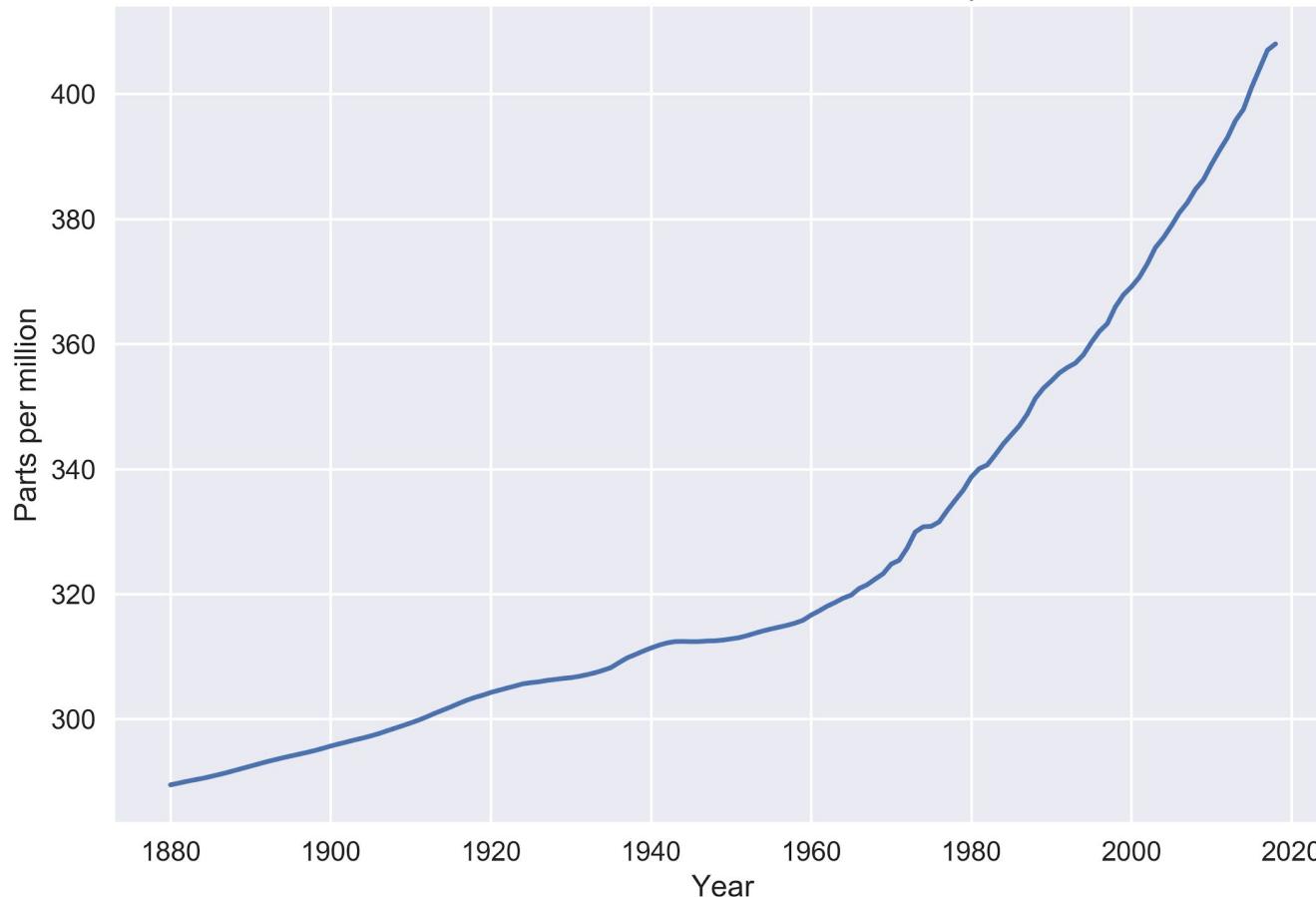
# Climate change and the science behind emissions

Jesse Murray

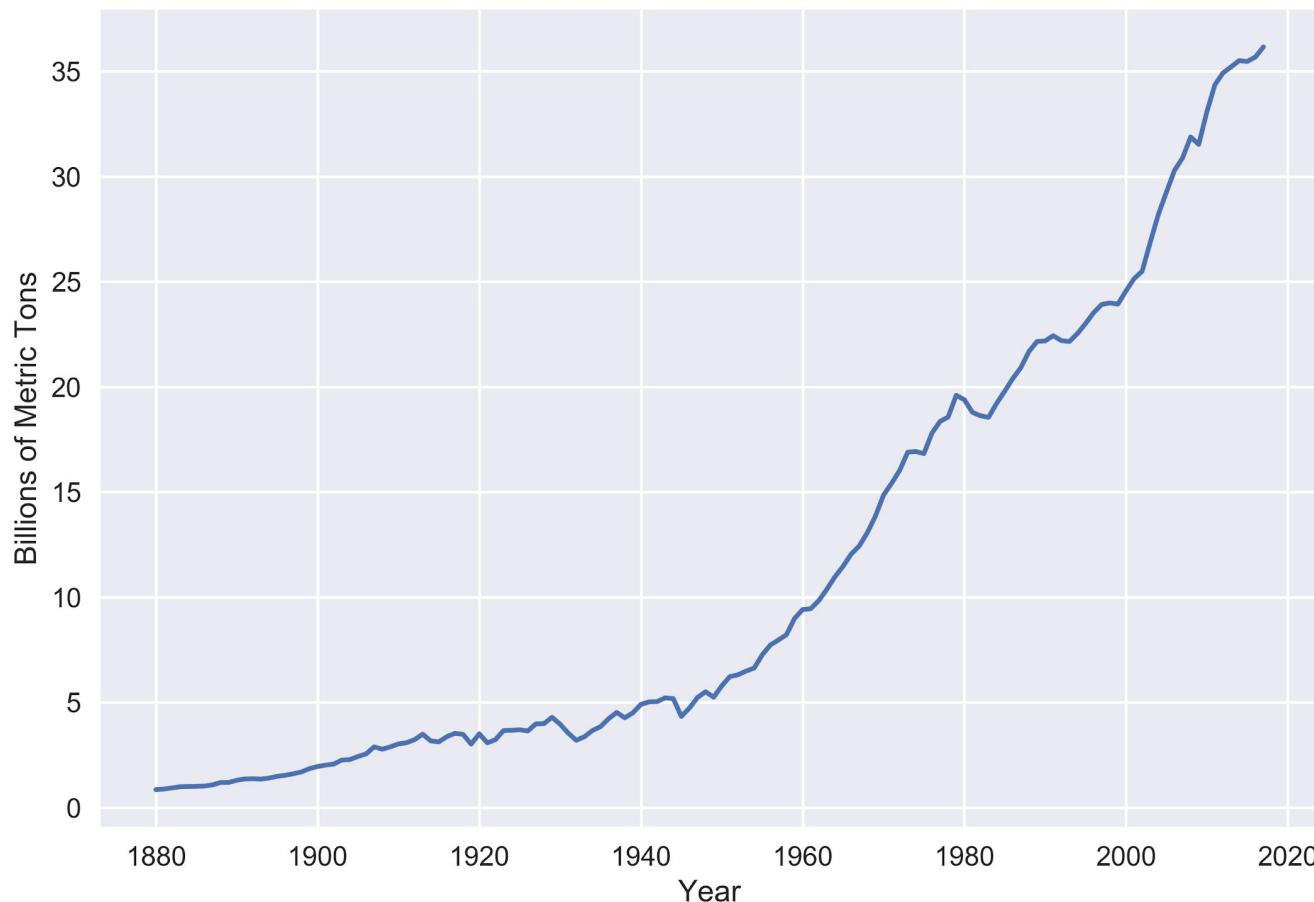
Global Average Temperature Relative to 1880 Temperature



## Global CO<sub>2</sub> Concentration in the Atmosphere



## Annual CO2 Emissions



# Going over 1.5 °C 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 1.5°C?

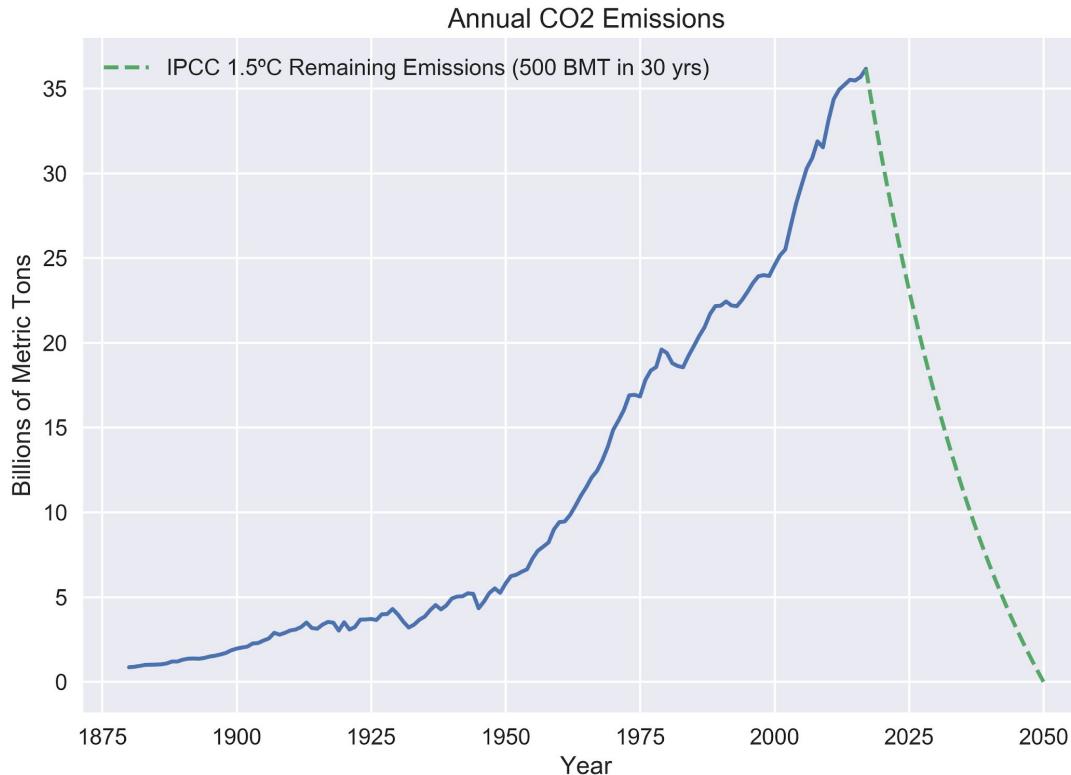
Most attention has gone towards an **emissions-only** approach

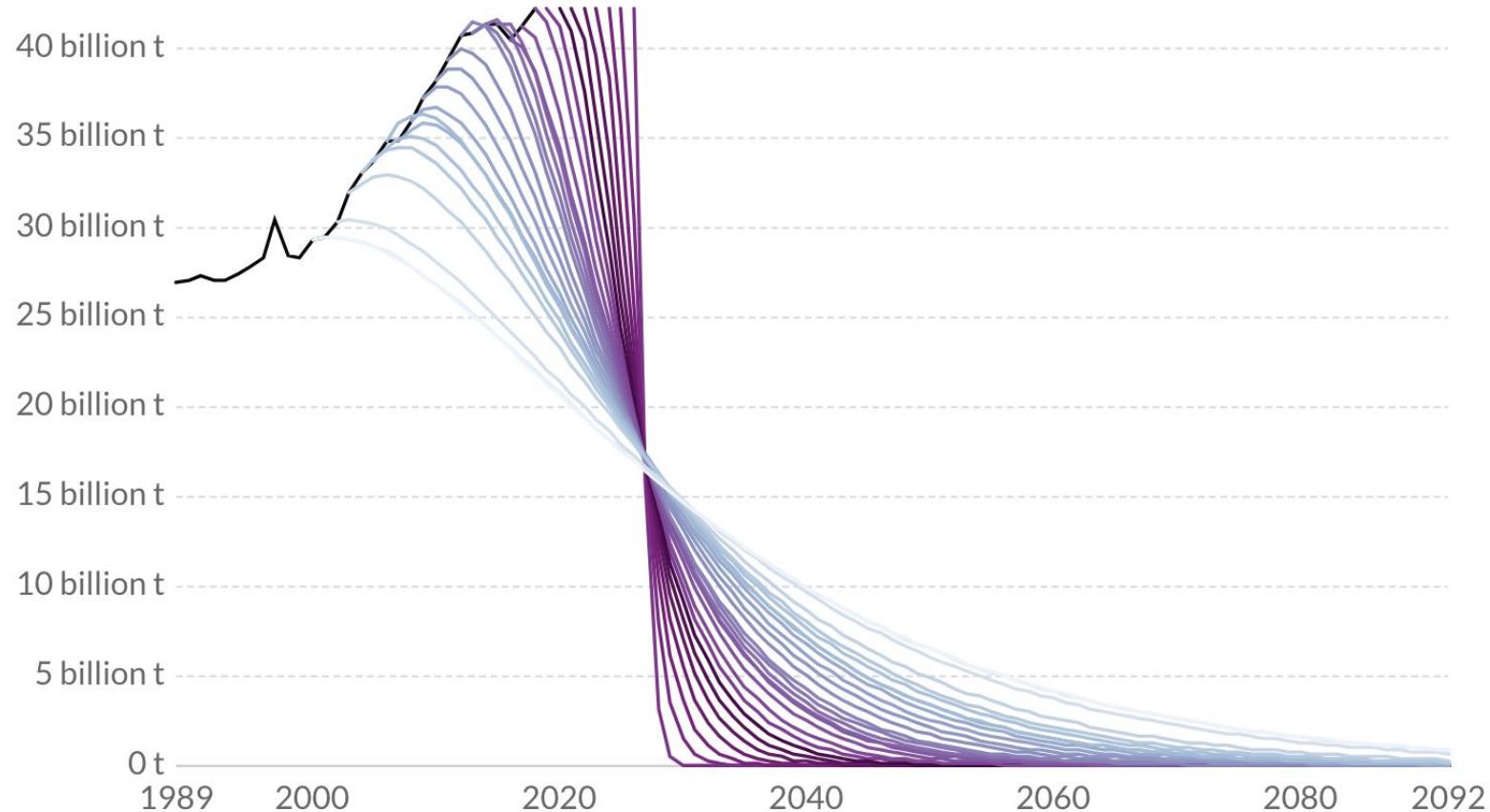
Through this approach:

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

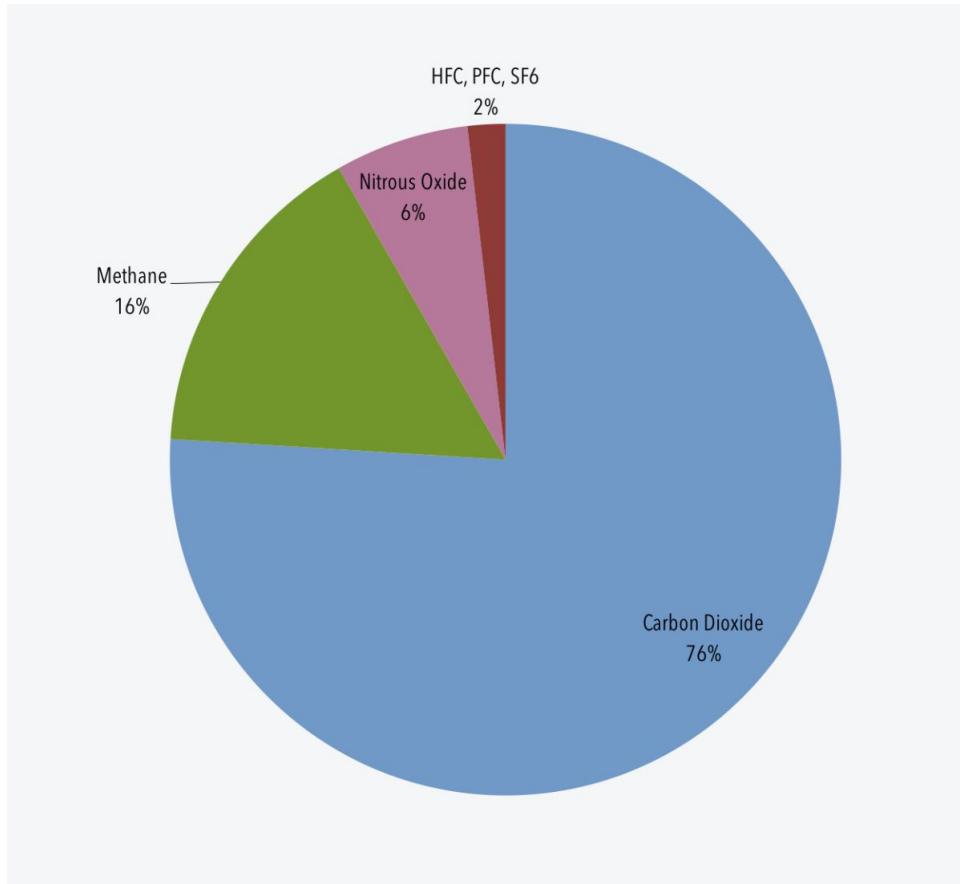
(IPCC)

# The emissions-only approach





# One quarter of emissions are not carbon dioxide



# The three decades ahead

We need to **understand** what's behind  
greenhouse gas emissions

To know what needs to happen

For emissions to reach **zero** in 30 years



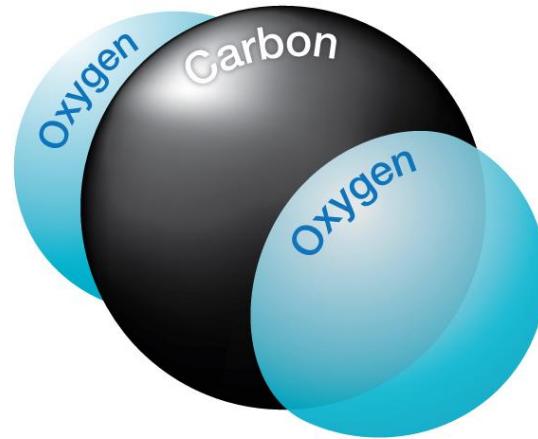
# Why do humans emit so much greenhouse gas?

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...

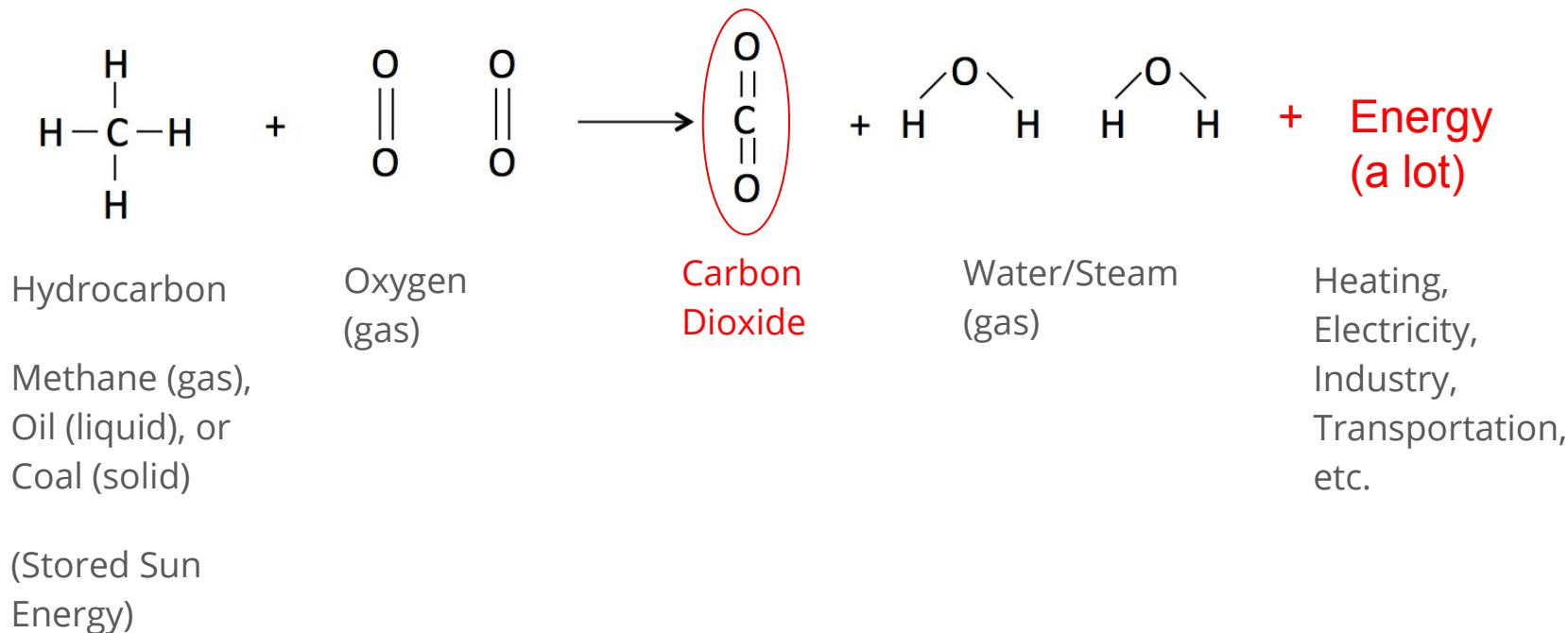
Humans need only about 2000 calories of energy each day for food, which is about **100 Watts**

But humans actually use about **10,000 Watts** in developed countries  
(100x more than needed for food)

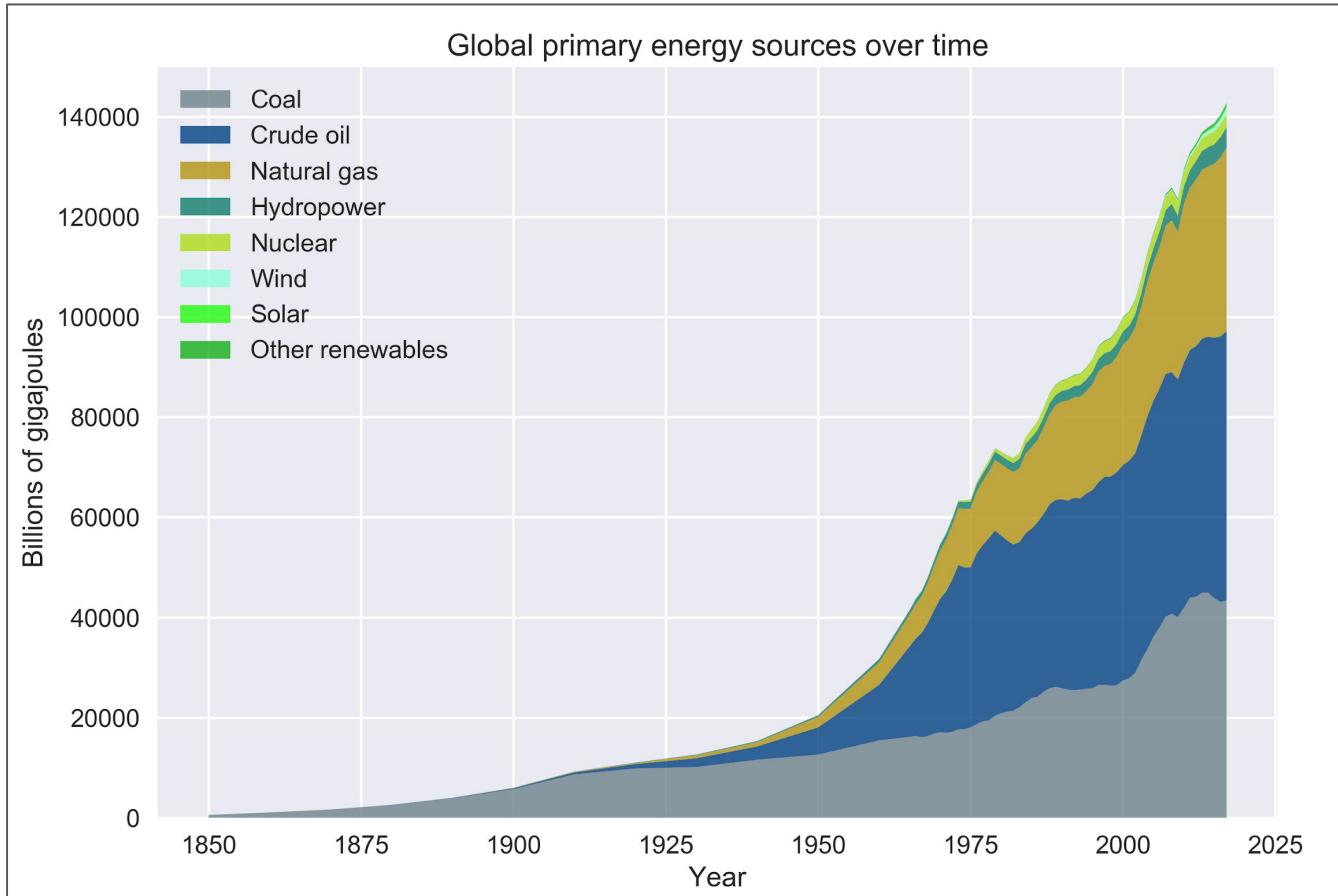
# Everything requires energy

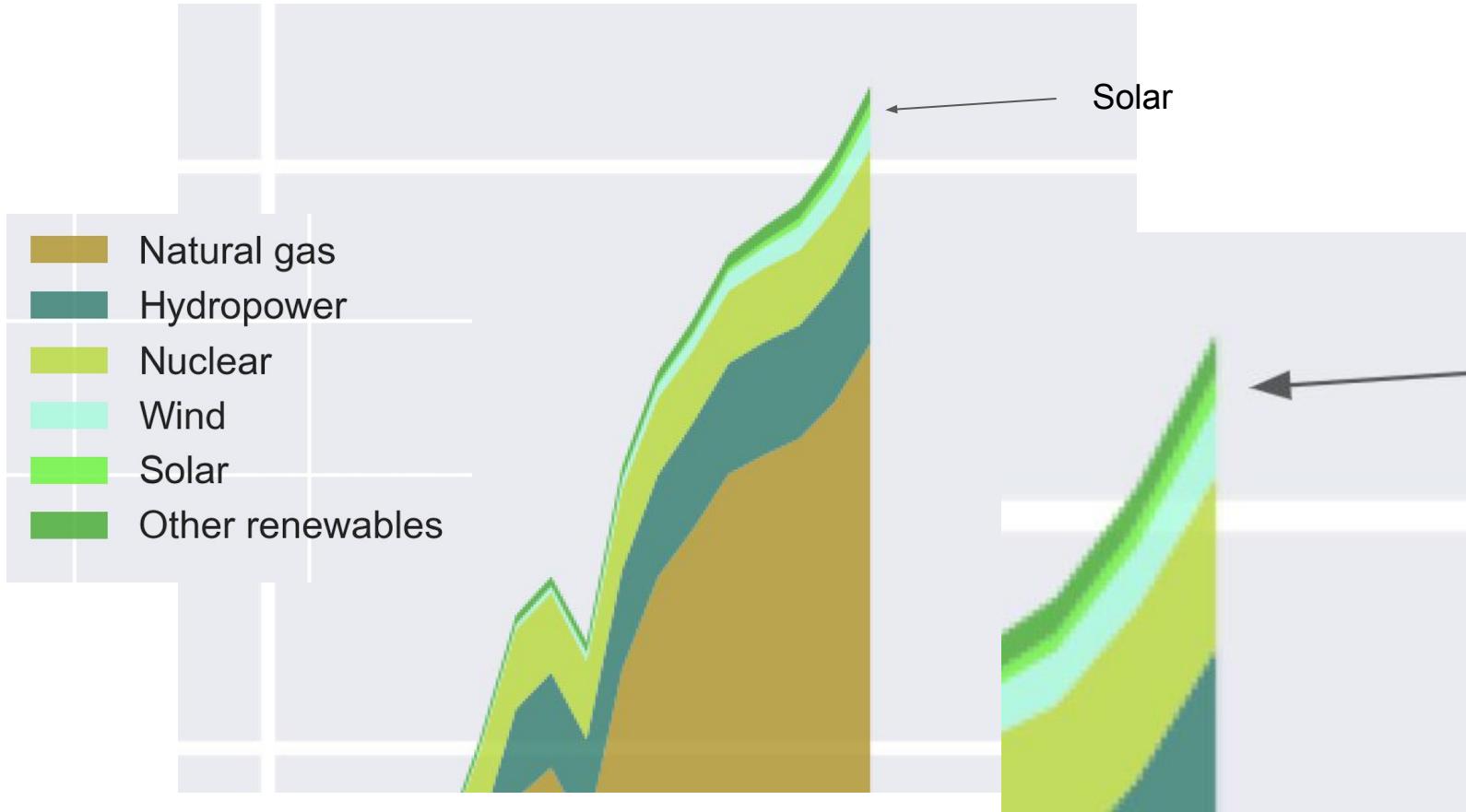
- **Manufacturing**
  - Most materials are made with significant heat,  $> 1000 \text{ } ^\circ\text{C}$
  - As a result, they have significant **embedded energies** - buildings are the biggest component
- **Shipping Transportation**
  - Range and capacity need to be maximized - requires substantial energy density
- **Human Transportation**
  - Air travel *requires* a significant threshold energy density
- **Heating**
  - Very energy-intensive, includes water heating, stove flame, and dryers
  - 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



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





# 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<sup>2</sup>
  - Coal/Oil: 1,000 to 10,000 W/m<sup>2</sup>
  - 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

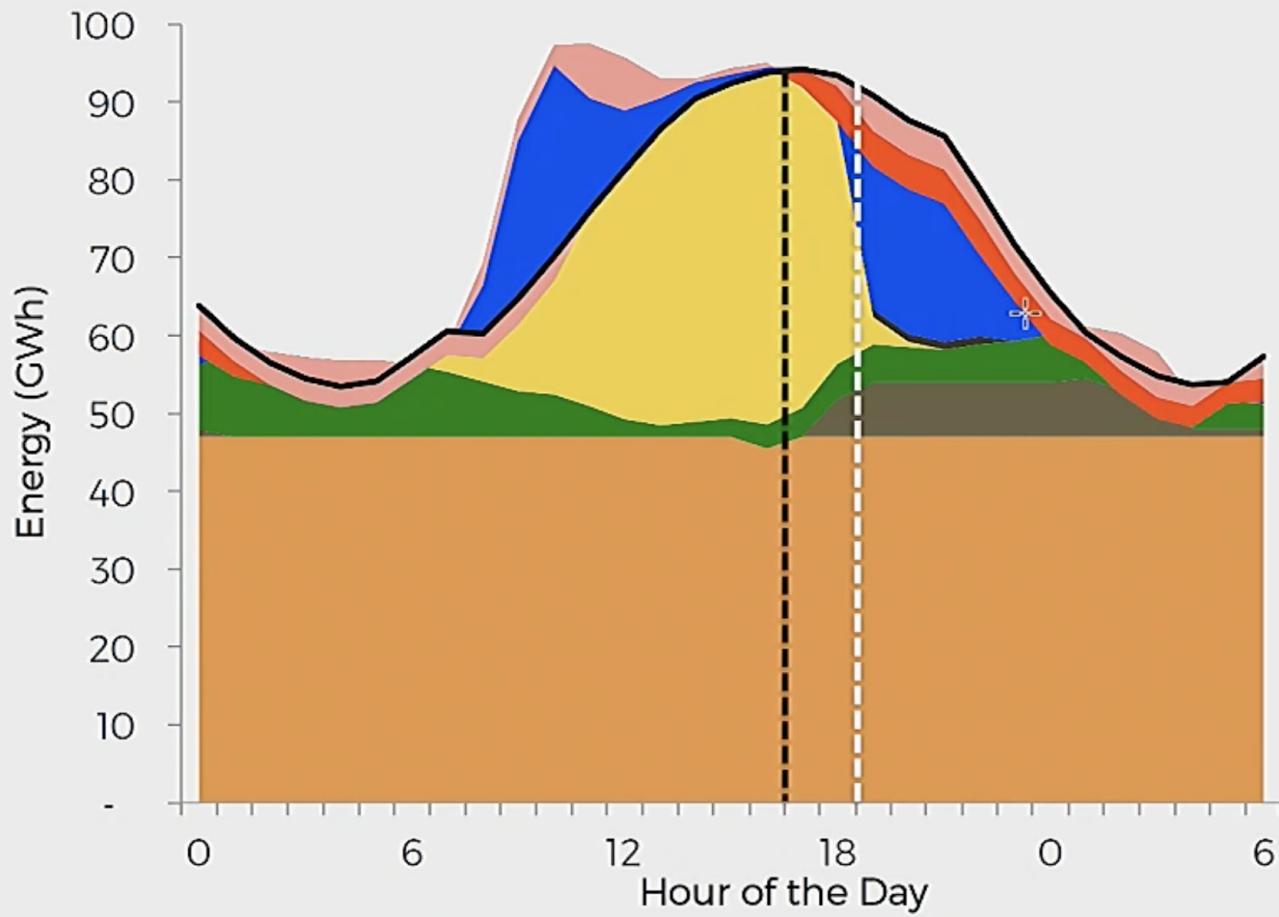
# Let's talk about electricity (~25% of emissions)

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

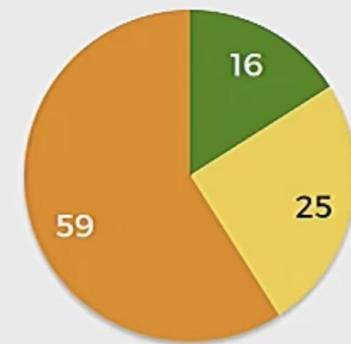
As a result, solar and wind **cannot** scale unless **intermittency** problem is solved

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

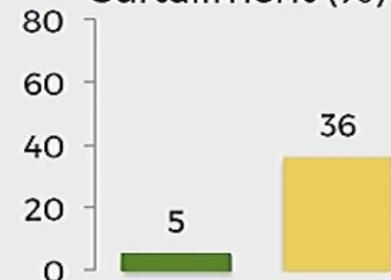
The greater the nuclear component, the less miraculous storage and transmission need to be



Annual Energy Share (%)



Annual Marginal Curtailment (%)



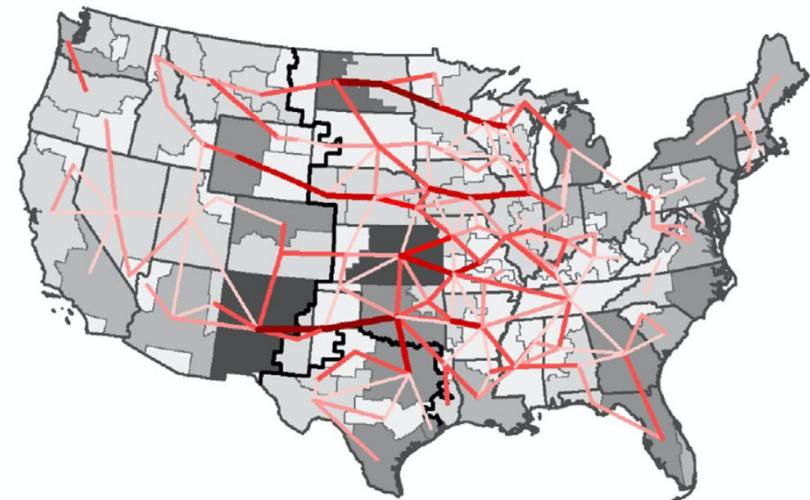
Nuclear **would** solve the electricity component, but rapid global deployment is unlikely



# 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



Mai et al. 2014

# Seasonal storage requirements (without nuclear)

Energy storage capacity required in 100% renewable energy scenarios for U.S. deep decarbonization



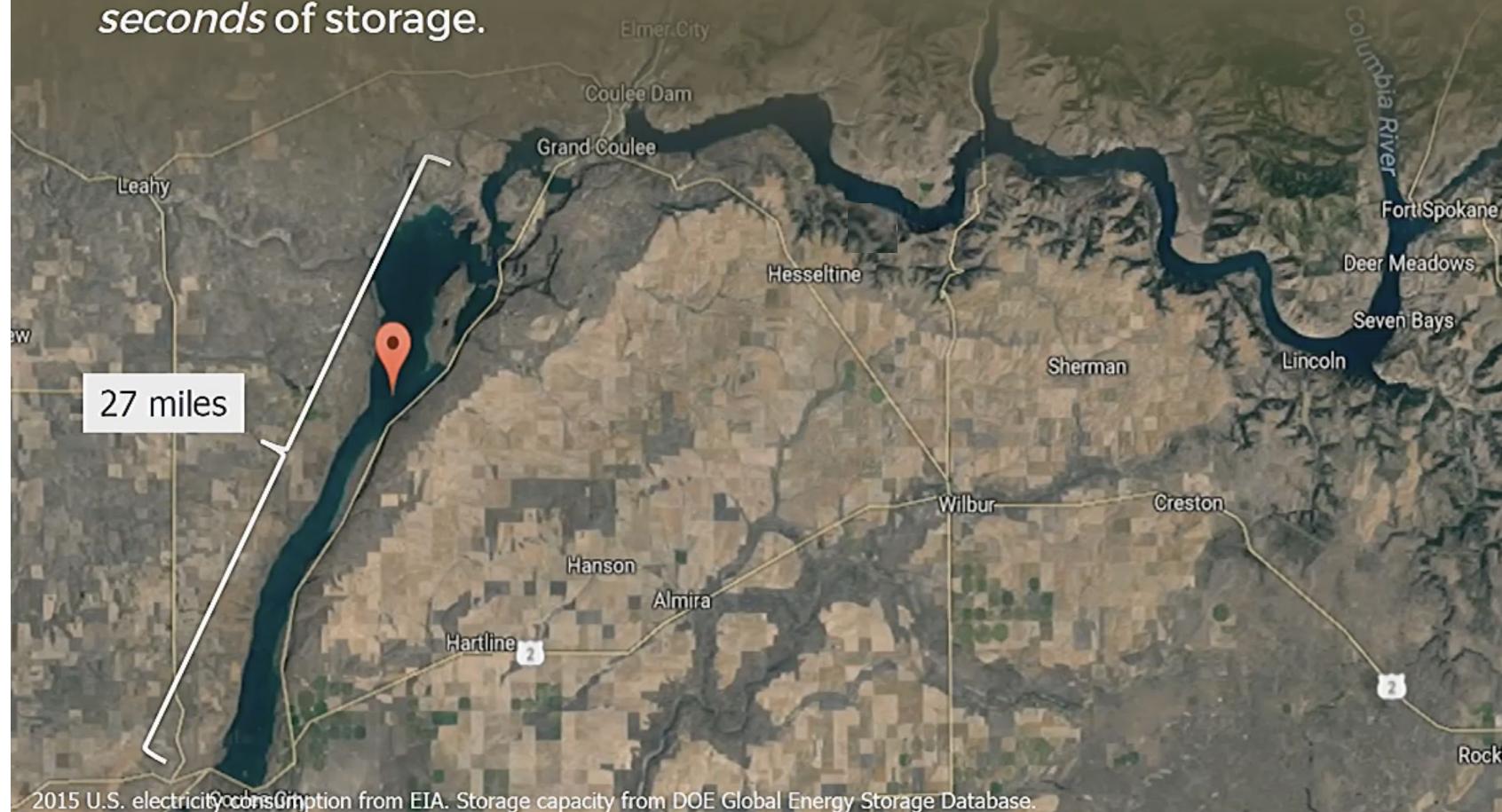
Graphic source: Jenkins & Therntsrom 2017. Deep Decarbonization of the Electric Power Sector: Insights from Recent Literature. Energy Innovation Reform Project.

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.**



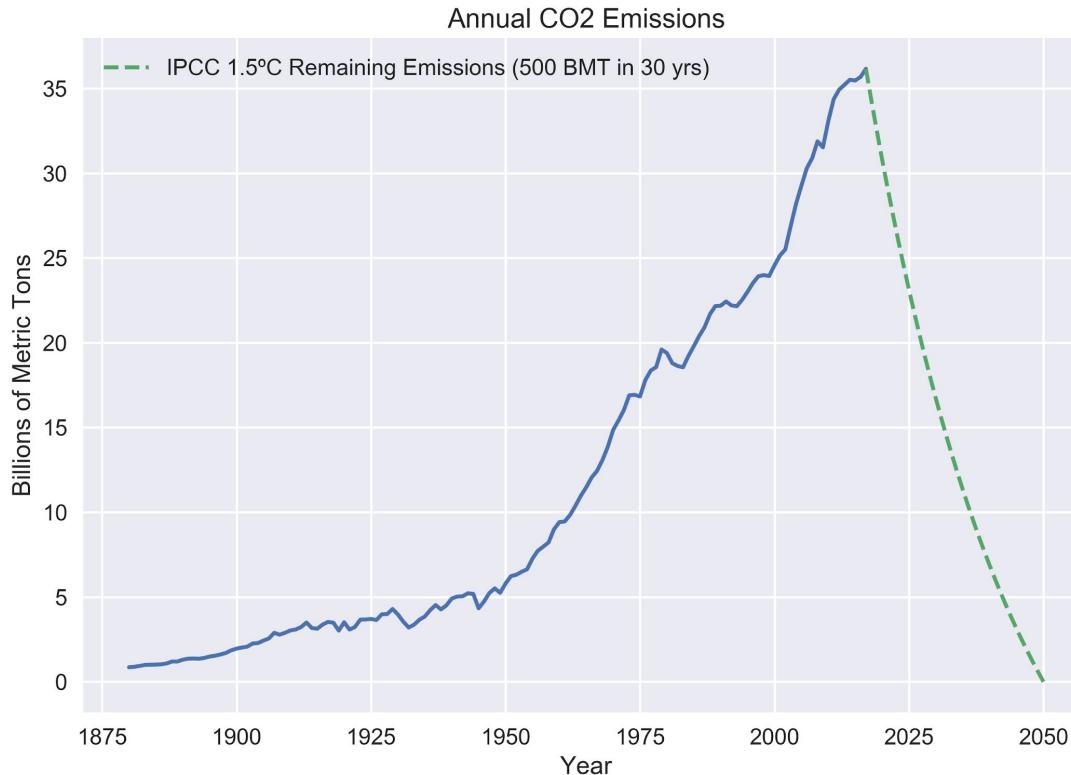
**John W. Keys III Pump-Generating Plant and Banks Lake Reservoir at Grand Coulee Dam: 25 GWh or 3 minutes and 30 seconds of storage.**



# 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)

# Back to emissions (need zero by 2050)



# Energy related emissions are about 60-70%

- **Transportation (14%)**

- Airplanes (1.8%)
- Container shipping (1.8%)
- Truck shipping (3.7%)
- Passenger cars (6.0%)
- Rail (0.7%)

- **Manufacturing (15%)**

- Cement (3.8%)
- Steel (5.2%)
- Ammonia fertilizer (0.8%)
- Other Industry (5.6%)

- **Electricity (25%)**

- **Heating (11%)**



# Non-energy related emissions are about 30-40%

(what solar and wind cannot solve)

- **CO<sub>2</sub> emitted from chemical *reactions* to make *products* (3.4%)**

- Cement
- Steel
- Plastic
- Fertilizer
- Other Chemicals

Cement Equation



- **Livestock (6%)**

- Dairy
- Beef

- **Deforestation (12%)**

- **Agriculture Soil Use, N<sub>2</sub>O (6%)**

- **Landfills (2%)**

# Energy density

The amount of energy per weight  
(Measured in joules per kilogram)

**Very important in transportation**



# Container shipping (~2% of emissions)

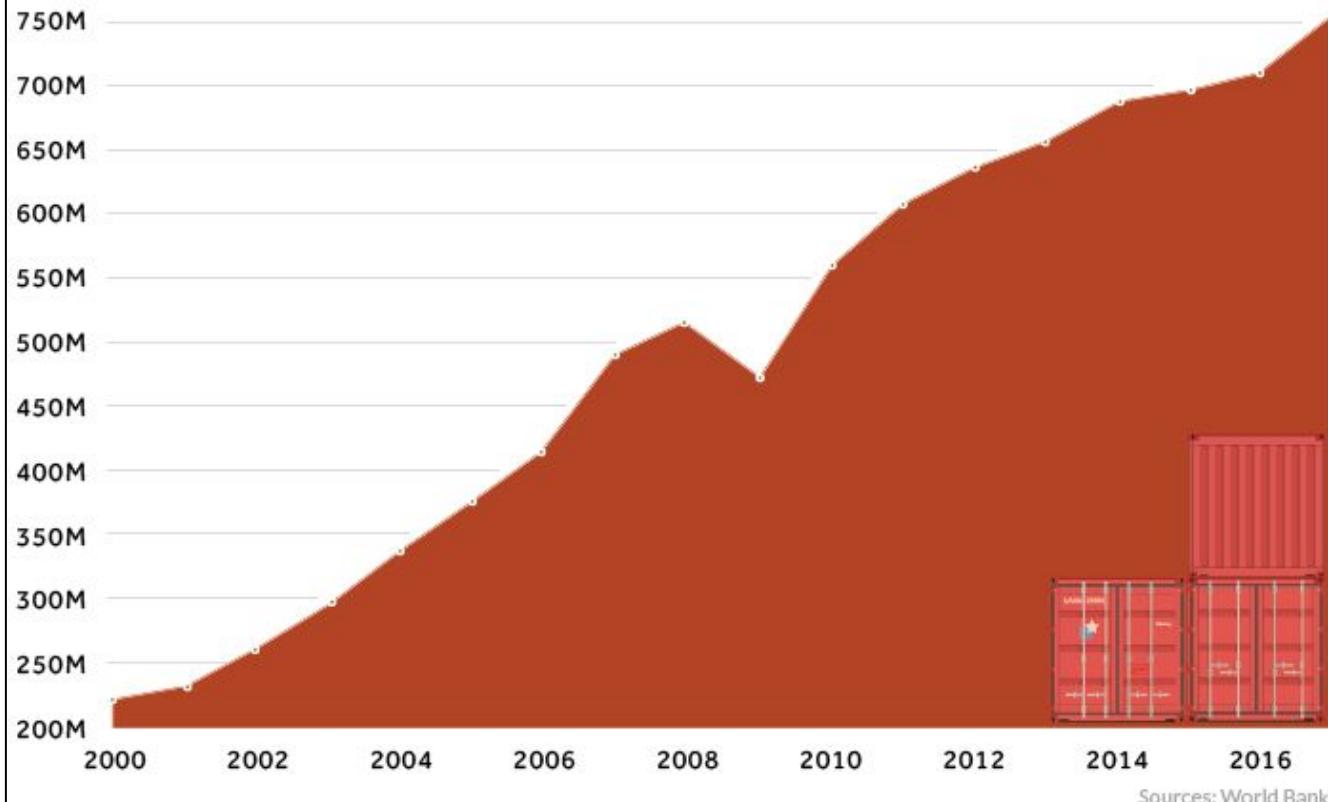
(Comparing the first battery-powered to a standard container ship)

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

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 PORT TRAFFIC (TEU)



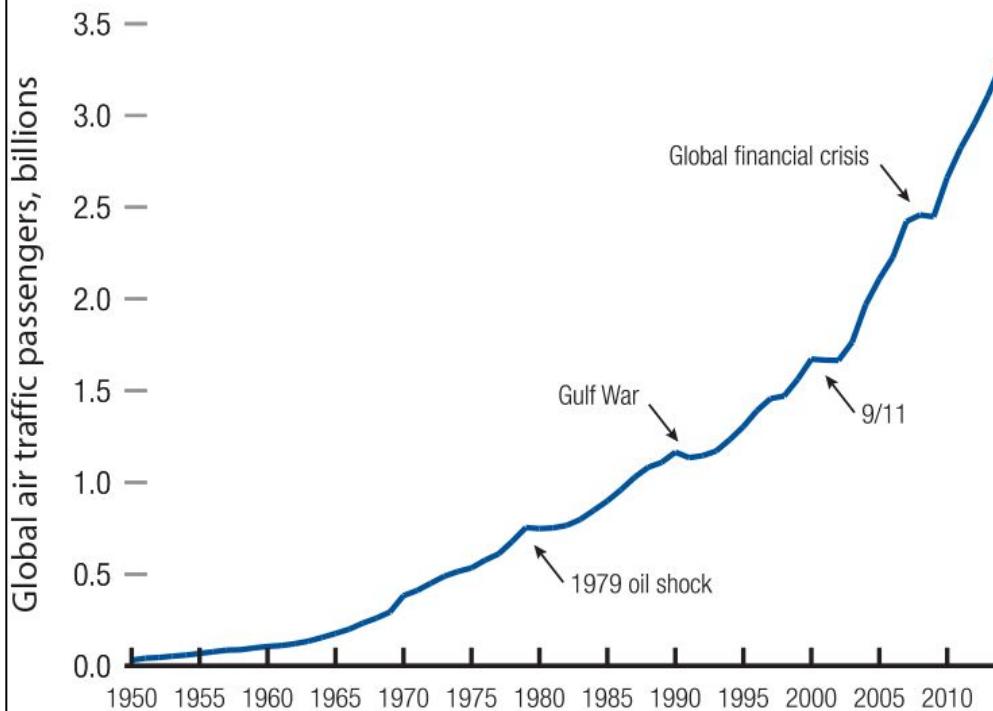
# Airplanes (~2% of emissions)

- 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



**Figure 1: Global air passenger traffic trend, 1950-2014**

(IATA Forecast for 2014)



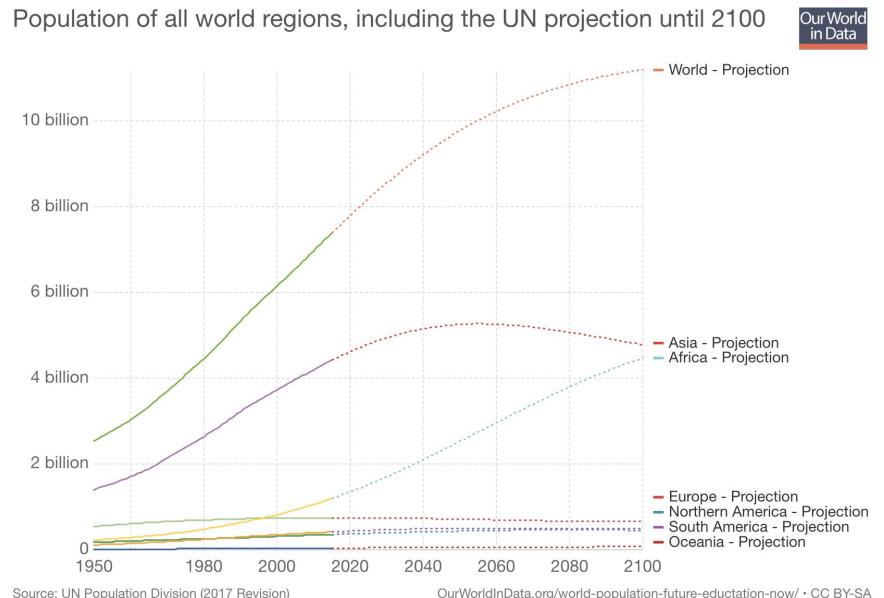
# Land use/agriculture/livestock (~24% of emissions)

- Carbon stored in **soil** and plants is released when forest is turned to cropland. (12%)
- Synthetic fertilizers release NO<sub>2</sub> when broken down by microbes. Natural fertilizers release CO<sub>2</sub> and CH<sub>4</sub> when decomposing (no net difference). (6%)
- Grazing ruminants emit methane. (6%)



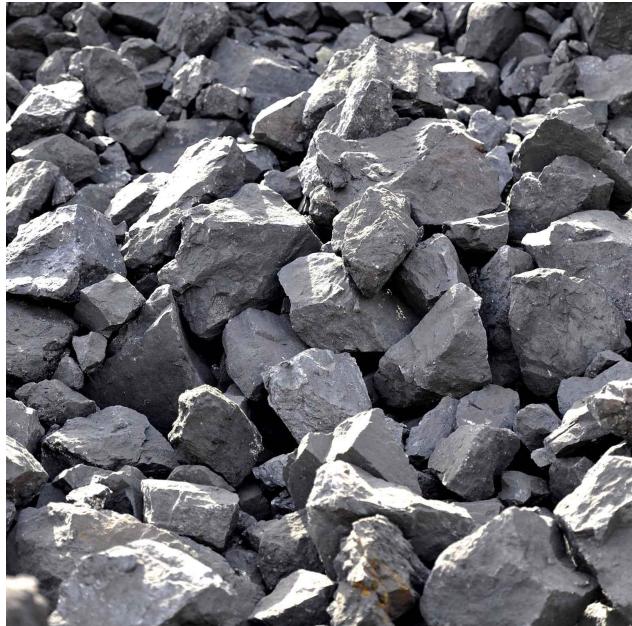
# Long term challenges in land-use component

- 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



# The story behind steel (~5% 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** (coal with little impurities)

Coke Oven

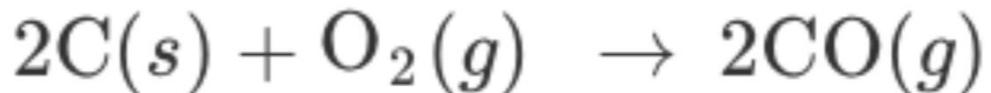


Coke



# Chemical reactions to make steel

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



Coke

Oxygen

Carbon monoxide

Then, use the carbon monoxide to remove the oxygen from iron oxide to get pure iron (steel)



Iron ore  
(iron oxide)

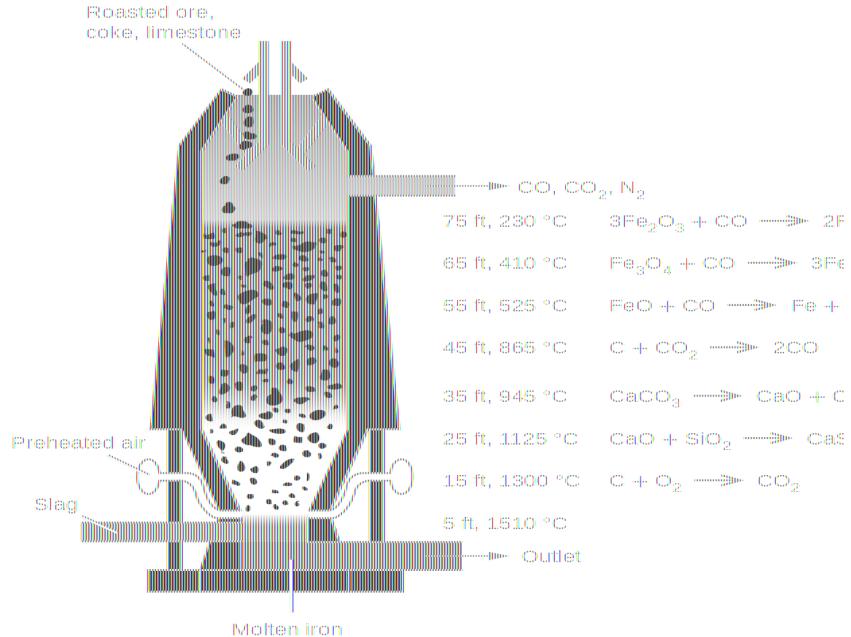
Carbon monoxide

Steel

Carbon Dioxide

# Chemical reaction occurs in blast furnace

- Heated to >1,800 °C
- Burn limestone to remove other impurities
- Molten pig iron is then decarbonized to make steel



(Started with iron ore and coal)

Steel



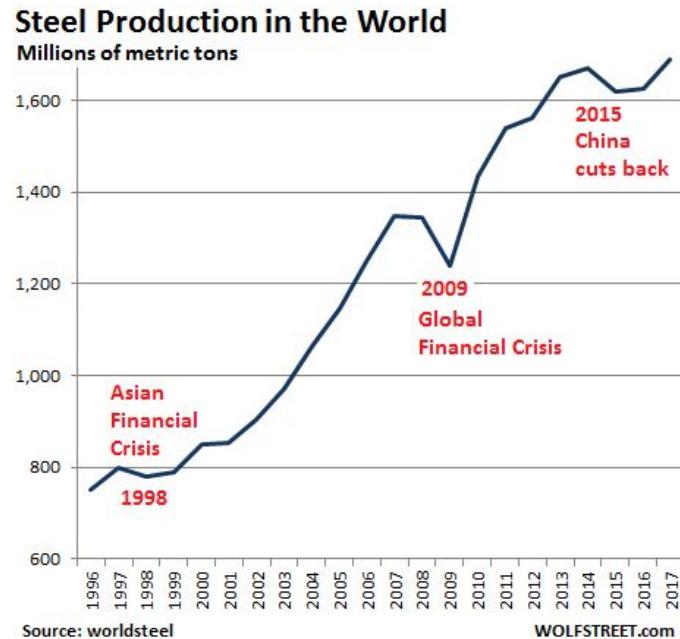
Carbon dioxide



# 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



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

Limestone



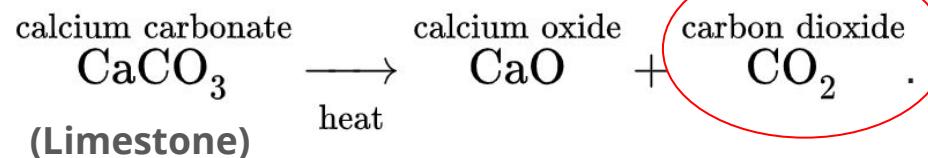
# Where it begins

Limestone quarry

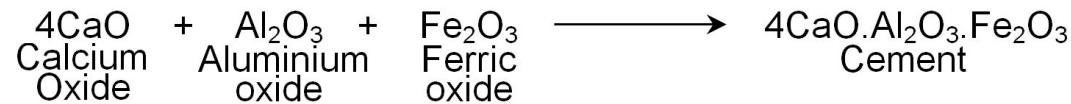


# Chemical reactions to make cement

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

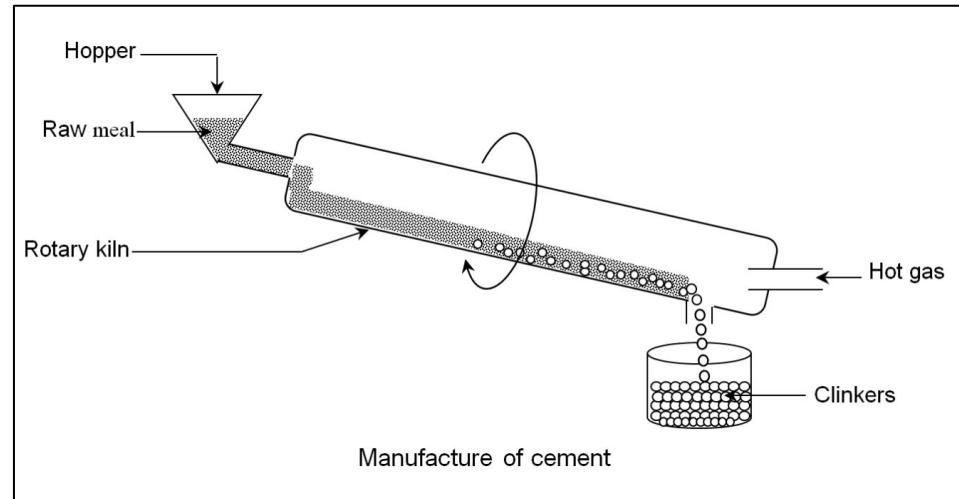


Then, react calcium oxide with other reactants to make cement



# Chemical reactions occurs in cement kiln

- Heated from 70 °C to 1,500 °C
- Kiln is spun to form clinkers



# Kiln is fired with coal

- Bright hot flame needed
- Coal produces very bright flame at  
2050 °C

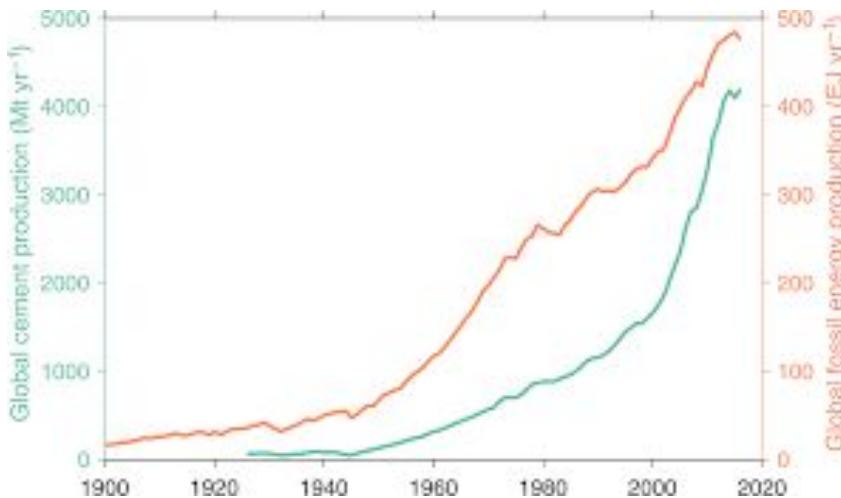


# Cement kiln



# 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 plastic (~1% of emissions)

Plastic is made from crude oil

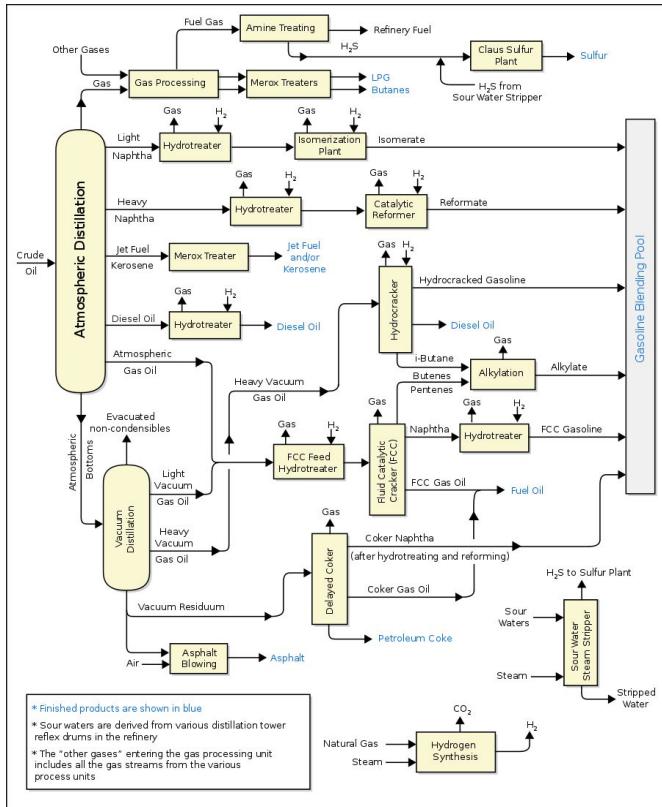


# Oil refineries (~3% of emissions)

- Oil comes out of the ground as crude oil

Oil is separated at 600°C to make:

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

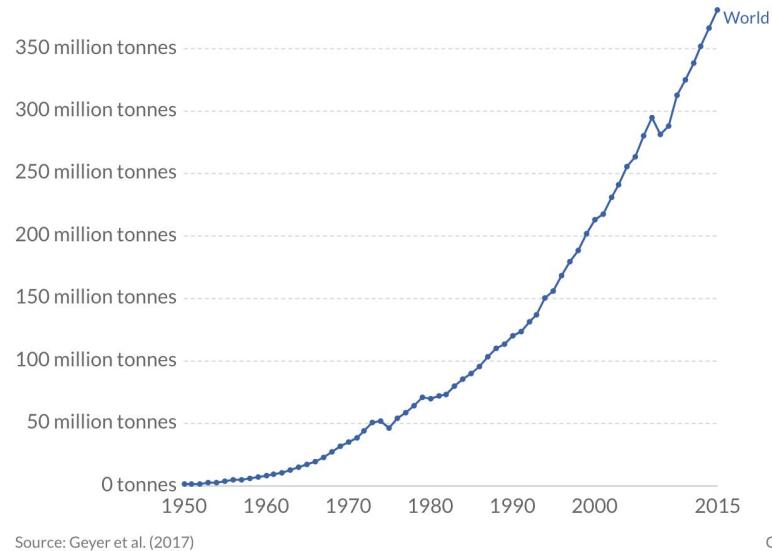


# Oil refinery



# Plastic is important, and growing

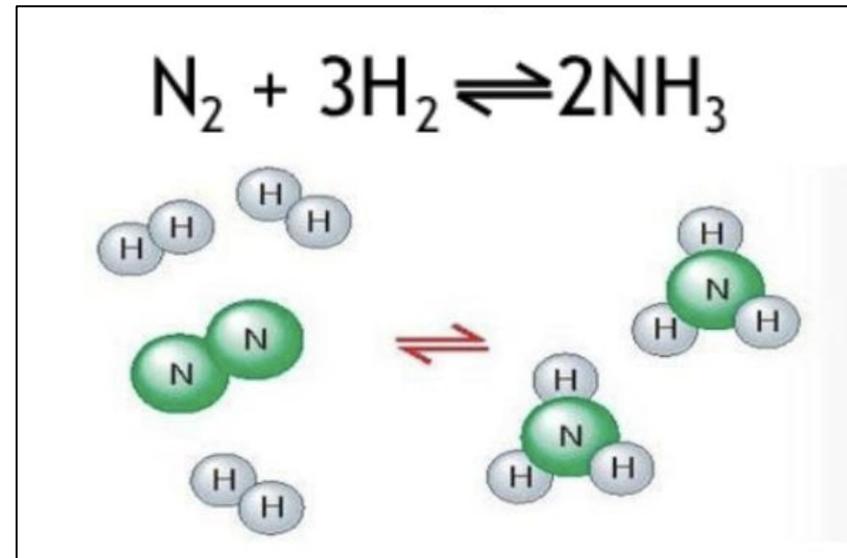
- Light malleable material
  - Important in shipping
  - Cars would be 3x heavier w/out plastic
- Plastic parts are ubiquitous
  - Appliances
  - Computers
  - Machines
  - Furniture
- Sterile medical equipment
- Consumer products
  - Salient, but small component



CC BY

# Ammonia fertilizer (~1% of emissions)

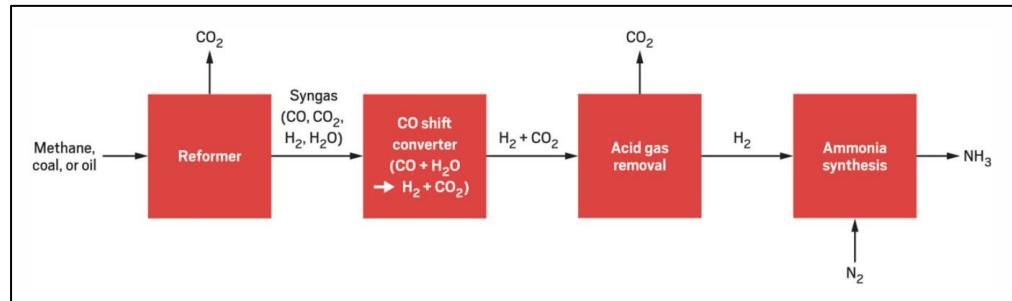
- Nitrogen is needed to live
- There's only enough nitrogen in the human and domestic animal nitrogen cycle to feed 45% of the world population
- So, remaining nitrogen is obtained from atmospheric N<sub>2</sub>



# Chemical reactions to make ammonia fertilizer

The Haber-Bosch process:

- Hydrogen in reaction comes from combusting fossil fuel
  - Coal
  - Oil
  - Natural gas
- Very energy intensive
  - 500 °C
  - 200x atmospheric pressure



# Haber-Bosch factory



45% of the world population couldn't eat food without the Haber-Bosch process (~1% of emissions)



*A small price to pay for salvation.*

# Four industrial pillars of civilization

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



# Wind turbines are **not yet** renewable

(Carbon emitting chemical reactions and embedded fossil fuel energies)

- **Steel** tower
- **Concrete** foundation
- **Plastic** blades
- **Oil** lubricants
- **Diesel** powered construction machinery
- **Glass-fiber** laminations
  - Made in > 1,700°C 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 technologies)



# Policies that would help, but not guarantee zero

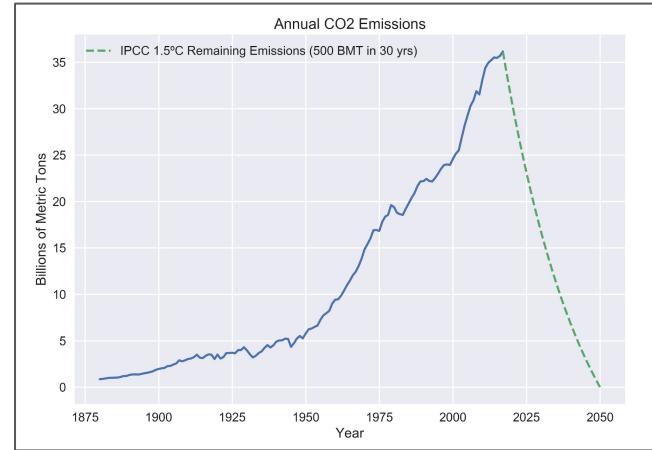
- **Majorly** fund research and development
  - Triple or quadruple current budgets
  - Hydrogen fuel?
  - Generation IV nuclear?
- Revenue neutral carbon price
  - Send currently missing price signal
  - Applicable to wealthy countries



# Is the emissions-only approach realistic?

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

1. Rapid inventions of new technologies
  - a. Reinvention of air travel, shipping, dairy and meat, landfilling
  - 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 100% global adoption of new technologies
  - a. Including 100% adoption of battery powered transportation and renewable electricity across 194 countries
3. New technologies **cannot** be more expensive as they need to be globally accessible

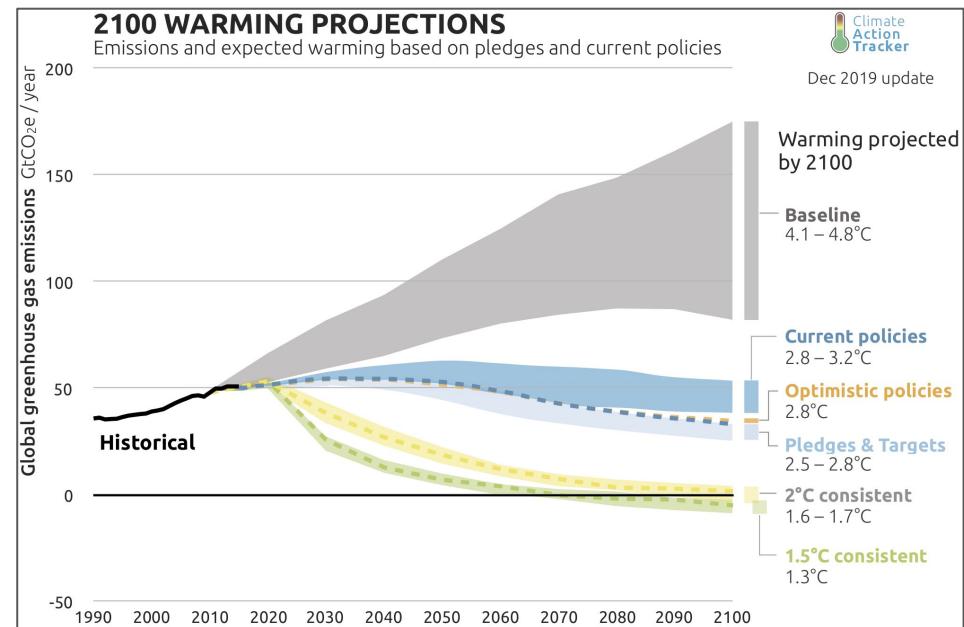


# What if it's 2050 and we haven't reached zero?

Do we allow the temperature rise to continue past 1.5 °C?

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

2 °C, 3 °C?



# 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

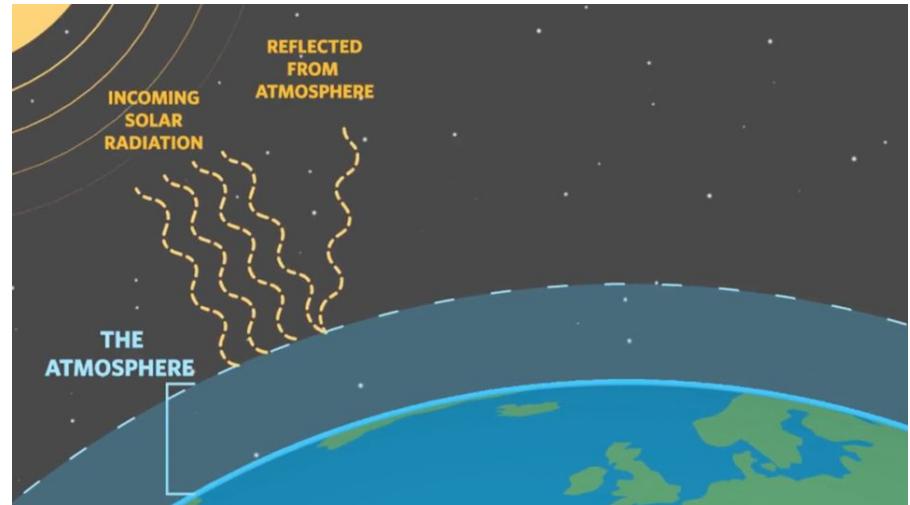
They'd work on solving the root cause and in the meantime, reduce the fever



# 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



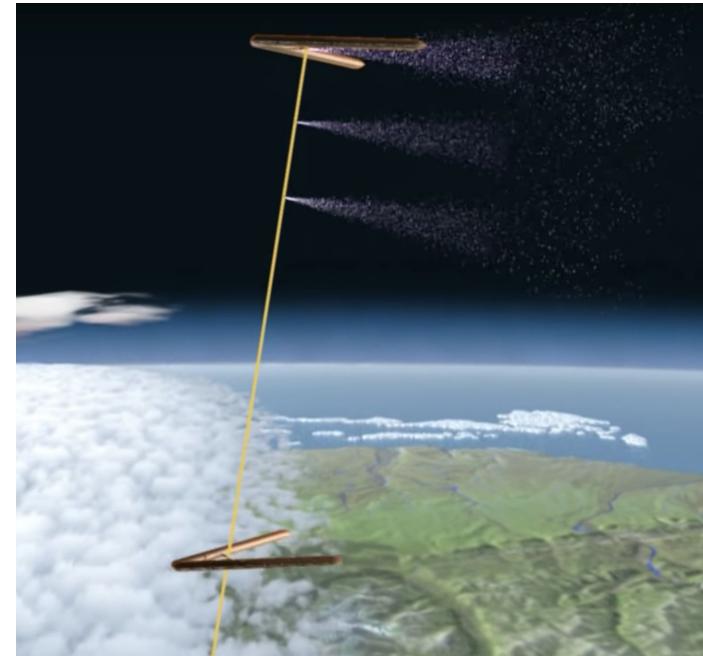
# We do this all the time (it's called solar radiation management)

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 ways

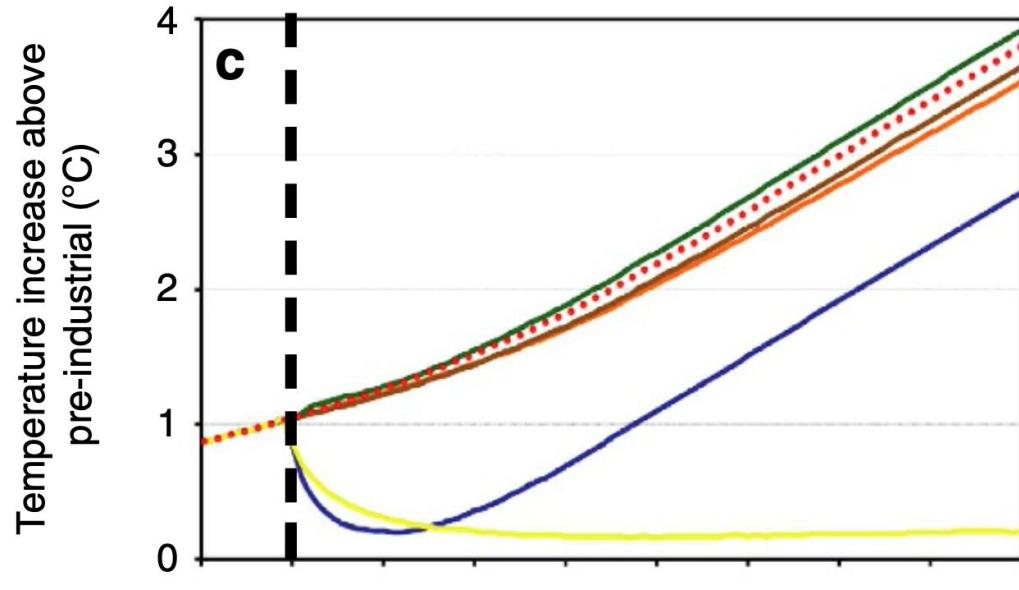
- Stratoshield "hose to the sky". One garden hose at the north pole, one at the south pole, both releasing sulfur
  - This has the advantage of having already occurred (1991 Mt. Pinatubo)
- 10,000 buoys in the ocean that kick up saltwater around which clouds form
- Lengthen coal plant chimneys
  - Doesn't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



Intellectual Ventures, 2009

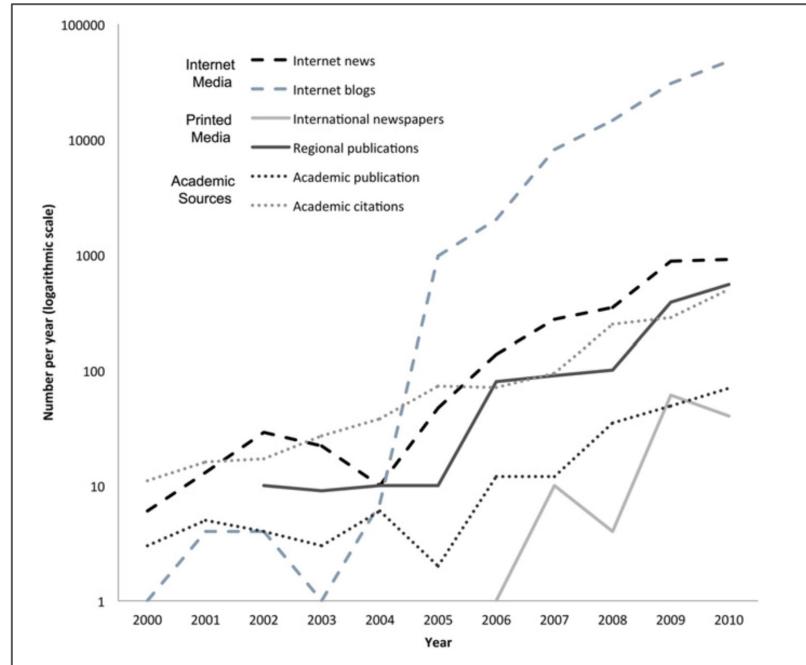
# Paper in *Nature* about geo-engineering methods

- No climate engineering •••
- Afforestation ■■■
- Ocean upwelling ■■■
- Ocean iron fertilization ■■■
- Solar radiation management ■■■
- Ocean alkalinization ■■■



Keller et al. 2014

# SRM has been gaining attention



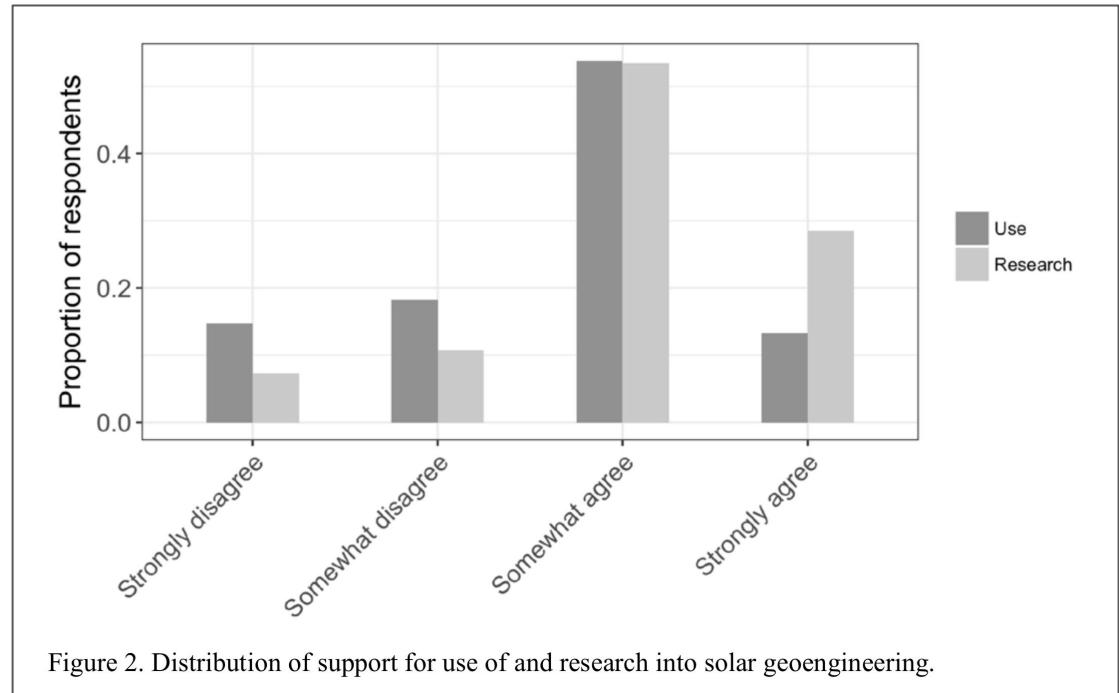
Mercer et al. 2011

# What does the public think of SRM?

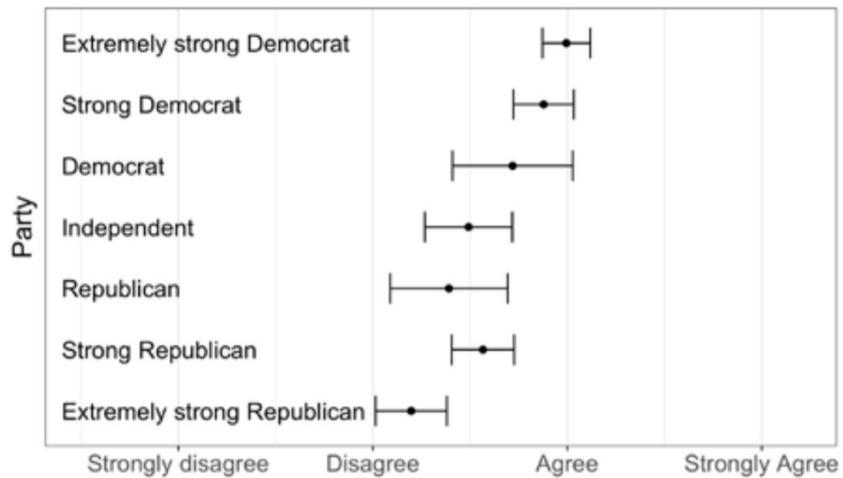
- 57% are ‘not at all familiar’

Upon reading about it:

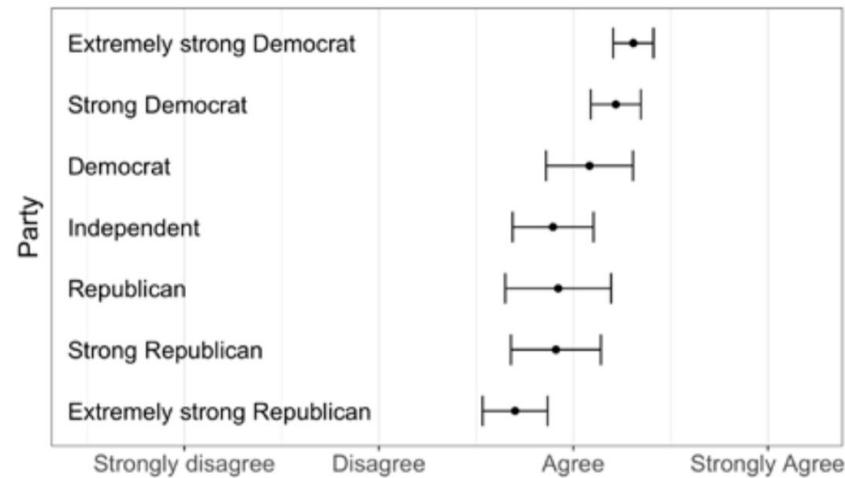
- 67% somewhat or strongly support **use**
- 81% somewhat or strongly support **research**



# 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

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

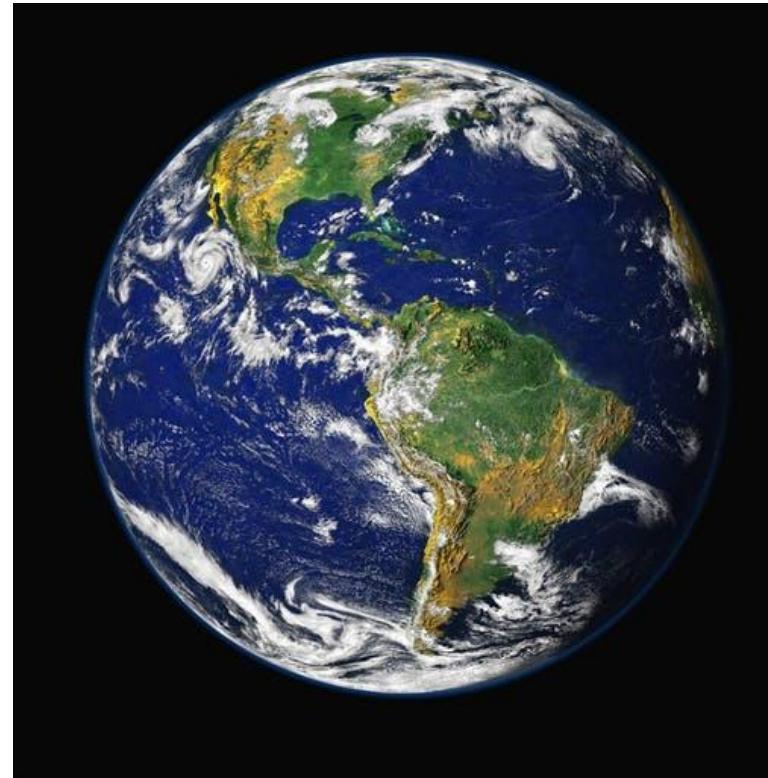
- SRM does not address the problem of ocean acidification
- But perhaps ocean acidification can be solved directly on its own
  - This is currently an area of research



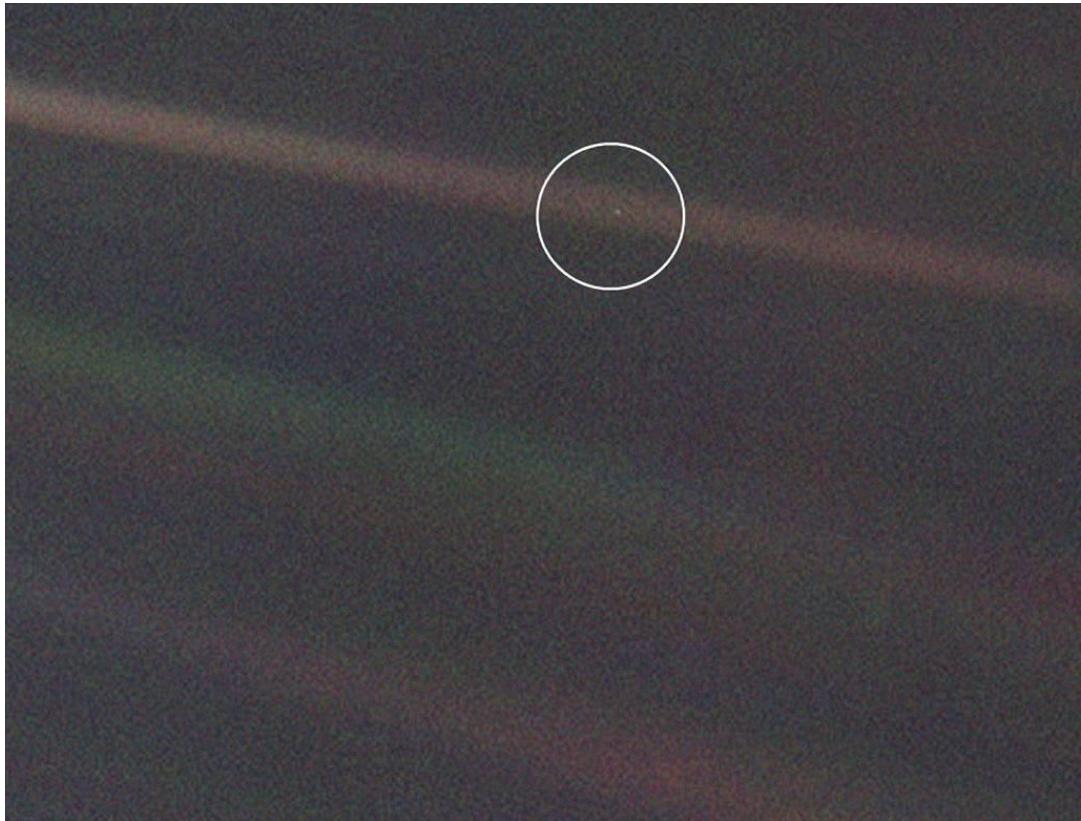
# SRM in the context of climate change

- SRM is **not** a replacement for decarbonization
- However, it **prevents** the ecological and human destruction that results from exceeding 1.5 °C

If 1.5 °C is unacceptable to us and zero emissions is not achieved by 2050, what other choice do we have?



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



# Acknowledgements

- Danie DiRuggiero

# Thank you

## References

- Fast, cheap, and imperfect? U.S. public opinion about solar geoengineering, Mahajan et al. 2018
- Public understanding of solar radiation management, Mercer et al. 2011
- Potential climate engineering effectiveness and side effects during a high carbon dioxide-emission scenario, Keller et al. 2014
- Envisioning a renewable electricity future for the United States, Mai et al. 2013
- Getting to Zero: Pathways to Zero Carbon Electricity Systems, Jenkins 2018
- Are Electric Planes Possible? Real Engineering
- Václav Smil at Driva Climate Investment Meeting 2019
- Industrial ammonia production emits more CO<sub>2</sub> than any other chemical-making reaction. Chemists want to change that, Boerner 2019
- What I See When I See a Wind turbine, Smil 2016
- Global Warming of 1.5 °C, IPCC 2018
- World GHG Emissions Flow Chart, World Resources Institute 2008
- Emissions and population data, Our World in Data











# New technologies **cannot** be more expensive

- Many people still live in poverty
  - 1 billion don't have access to electricity
  - 863 million live in slums
  - 4 billion live on less than \$8 a day
- What we all (I hope) believe:
  - These places should do whatever it takes to reduce malnutrition and starvation
  - It is unjust to place constraints on escaping poverty

