Freedom from Fossil Fuels

How we got here, what's at risk – and how we'll fix it

Twitter: @StephenMettler
Narrated Version: https://youtube.com/playlist?list=PLxB3jIOelwBHg4KgFZy3STiNpuIoDTk1t
More Info: https://skepticalscience.com/freedom-from-fossil-fuels.html

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These slides will walk through how to understand, evaluate, and address fossil fuel use and climate change

1 How We Got Here *Slides 3-9*

How the greenhouse effect works, human vs. natural CO_2 emissions, and Earth's pace of warming

2 What's at Risk *Slides 10-19*

Current and future threats that fossil fuels pose to humans, and their costs

3 How We'll Fix It *Slides 20-28*

Technologies that will allow us to move beyond fossil fuels, restore a stable climate, and secure our future

These slides are:

- A **politically neutral overview** of fossil fuels, climate science, and clean technology
- A **foundation for further research and a framework for putting it in context**

These slides are not:

- A budgetary or legislative **policy proposal**
- A case for **picking specific clean technologies**
- Groundbreaking for **those who already follow climate science closely**

Readers with a deep understanding of climate science are encouraged to skip ahead; *section introductions (slides 3, 10, and 20) provide slide-by-slide tables of contents*

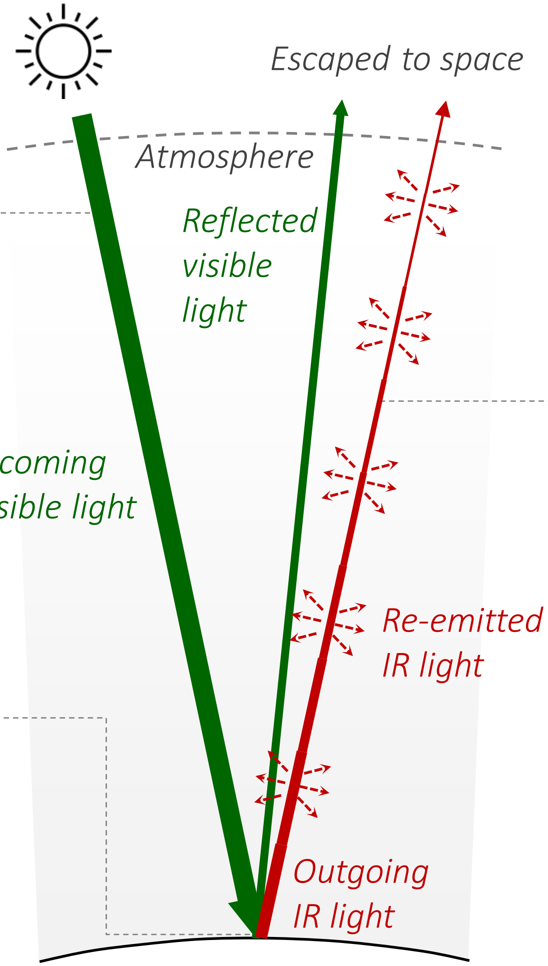
This section explores why, and how quickly, Earth's climate is warming

Key Argument

Humans' fossil fuel use has destabilized Earth's natural carbon balance, **heating our climate at an unprecedented pace**

Greenhouse gases work as a one-way door, letting more energy enter Earth's atmosphere than they let escape, so more greenhouse gases mean higher heat

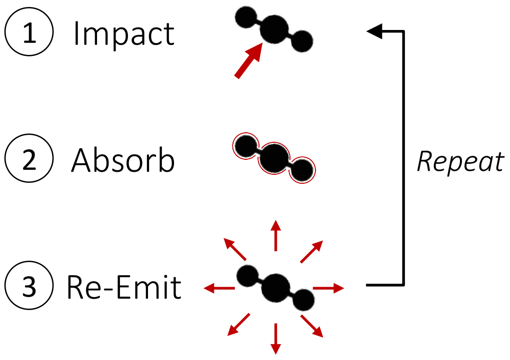
1 Visible sunlight passes straight through atmosphere



2 Some visible light is reflected by surface, but some is converted to infrared (IR)

Human eyes can't see IR, but we can feel it coming off a campfire or a hot stove

3 Greenhouse gases let visible light through but absorb IR, trapping its energy and warming the atmosphere[1]



① Impact

② Absorb

③ Re-Emit

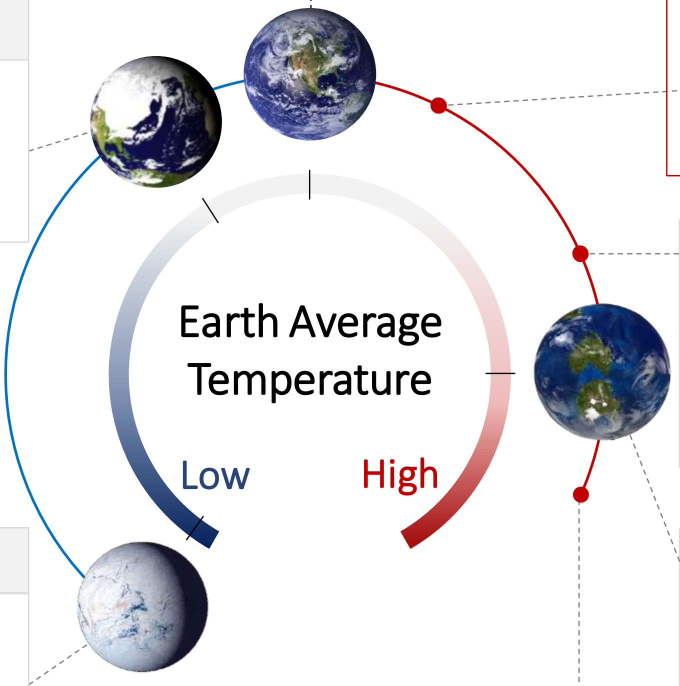
Repeat

Link for citations and additional notes

The amount of greenhouse gas, especially carbon dioxide (CO_2), in the atmosphere has been the core driver of climate variation over Earth's history

"Pre-Industrial" Baseline

1850-1900 Earth Average[3]



Last Ice Age -4°C

Peaked 20,000 years ago; ended with shifts in Earth's orbit and large volcanic CO_2 emissions[2]

"Snowball Earth" -25°C

750M years ago, Earth's interior absorbed almost all CO_2 from atmosphere, freezing surface[1]

WE ARE HERE

2020 Earth +1°C

Over 1/3 rise in atmospheric CO_2 since pre-industrial age[4]

Last Time at Today's CO_2 +3°C

3M years ago; the extra heat also resulted in 50+ feet higher seas[5]

Eocene Earth +7°C

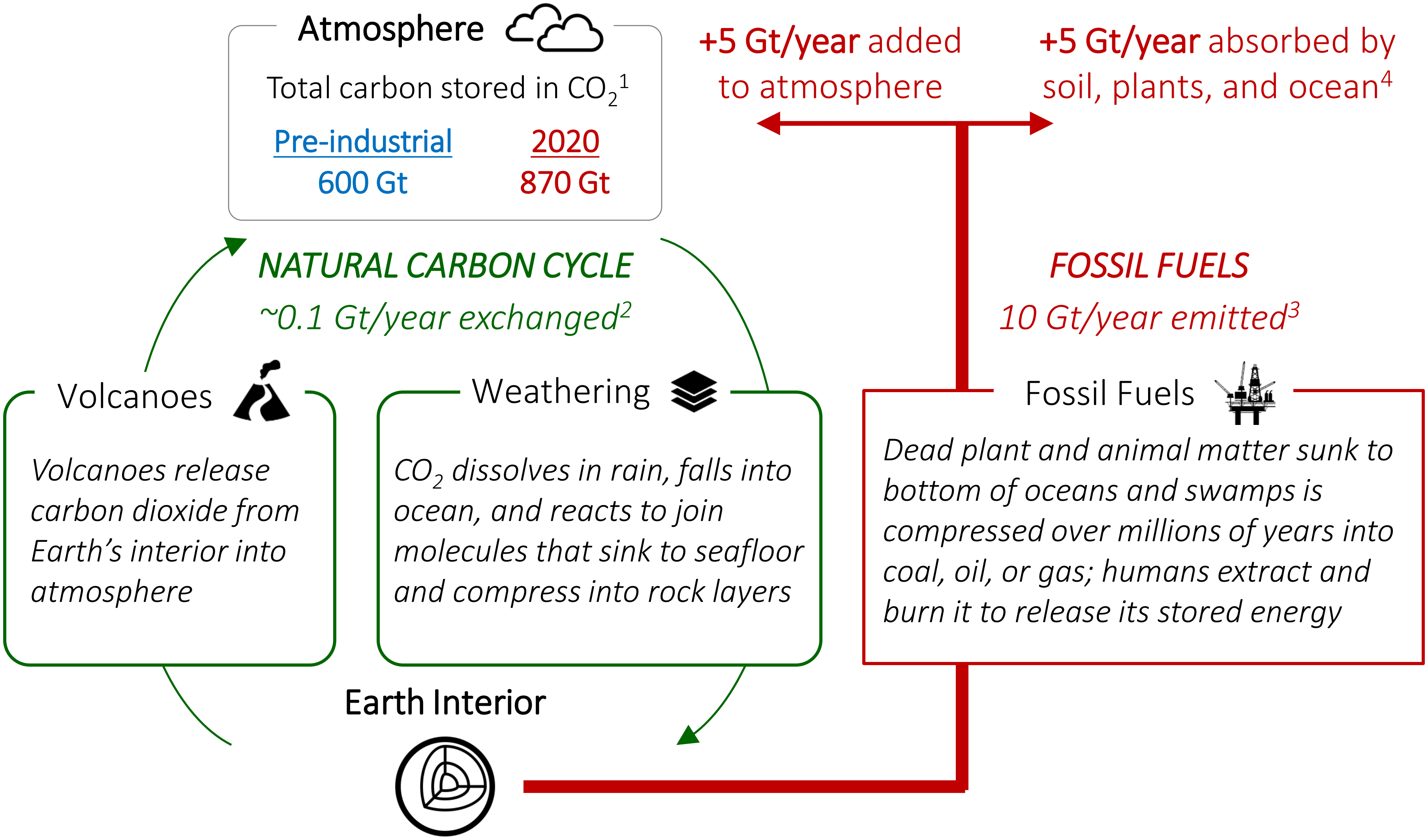
50M years ago, high CO_2 brought hot climate; the green, forested islands are Australia and Antarctica[6]

Worst-Case Earth +10°C

Burning all known fossil fuels could raise average temperature this much[7]

Temperatures are relative to the "Pre-Industrial" Baseline; -25°C=-45°F, -4°C=-7.2°F, +1°C=+1.8°F, +3°C=+5.4°F, +7°C=+12.6°F, +10°C=+18°F; link for citations and additional notes

Carbon moves naturally between Earth's interior and atmosphere, but human fossil fuel emissions massively exceed the natural cycle rate



Atmosphere

Total carbon stored in CO_2[1]

Pre-industrial	2020
600 Gt	870 Gt

+5 Gt/year added to atmosphere

+5 Gt/year absorbed by soil, plants, and ocean[4]

NATURAL CARBON CYCLE

~0.1 Gt/year exchanged[2]

FOSSIL FUELS

10 Gt/year emitted[3]

Volcanoes

Volcanoes release carbon dioxide from Earth's interior into atmosphere

Weathering

CO_2 dissolves in rain, falls into ocean, and reacts to join molecules that sink to seafloor and compress into rock layers

Fossil Fuels

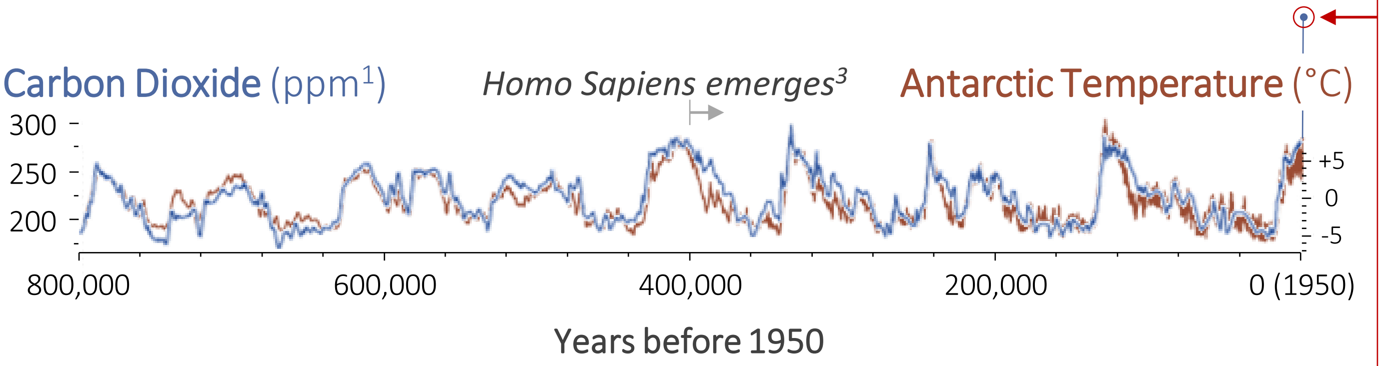
Dead plant and animal matter sunk to bottom of oceans and swamps is compressed over millions of years into coal, oil, or gas; humans extract and burn it to release its stored energy

Earth Interior

Gt = Gigatonne, 1 billion metric tons. Values are for carbon (C), which is 27% of a CO_2 molecule's mass, so humans emit ~10 Gt/year of C but ~40 Gt/year of CO_2. Link for citations and additional notes

Humans are raising atmospheric CO_2 at the fastest rate since before complex life evolved on Earth – if not in Earth's entire history

Atmospheric CO_2 and Antarctic Temperature Ice Core Data[1]



WE ARE HERE

2019 average CO_2
410 ppm[2]

We're raising CO_2 so fast that the line looks vertical on this timescale

Humans Are Crushing All-Time Emissions Records

Team Nature

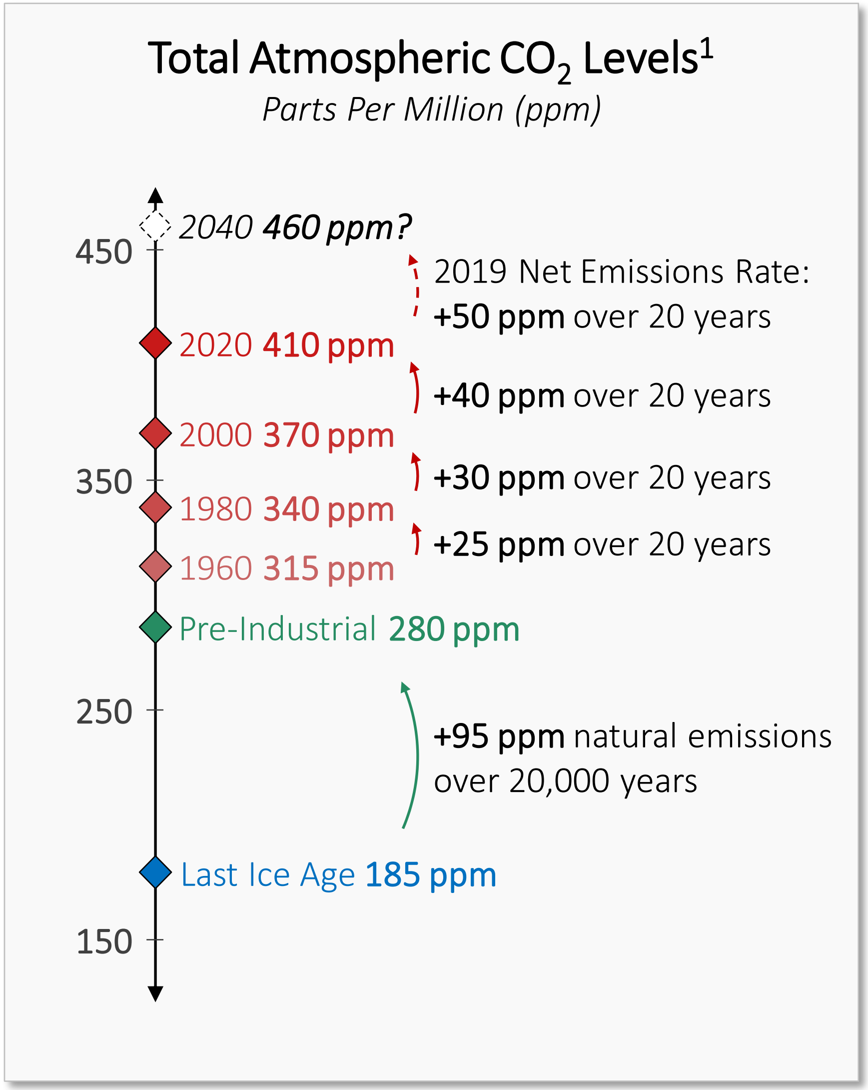
Paleocene-Eocene Thermal Maximum 55M years ago, most severe known natural heating event in Earth's history, peaked at **0.2-0.7 ppm/year emissions that at least doubled CO_2 over 6,000 years[4]**

Team Human

Adding around **2.5 ppm/year of CO_2 to the atmosphere,[5] we're on pace to double CO_2 over 150 years;[6]** if this rate has happened before on Earth, it was likely over 700M years ago, before complex animals evolved[7]

Link for citations and additional notes

Since the Industrial Age began, we've pumped more and more CO_2 into the atmosphere, driving global temperatures up faster and faster



Total Atmospheric CO_2 Levels[1]

Parts Per Million (ppm)

*2040 **460 ppm?***

2019 Net Emissions Rate:
+50 ppm over 20 years

2020 **410 ppm**

+40 ppm over 20 years

2000 **370 ppm**

+30 ppm over 20 years

1980 **340 ppm**

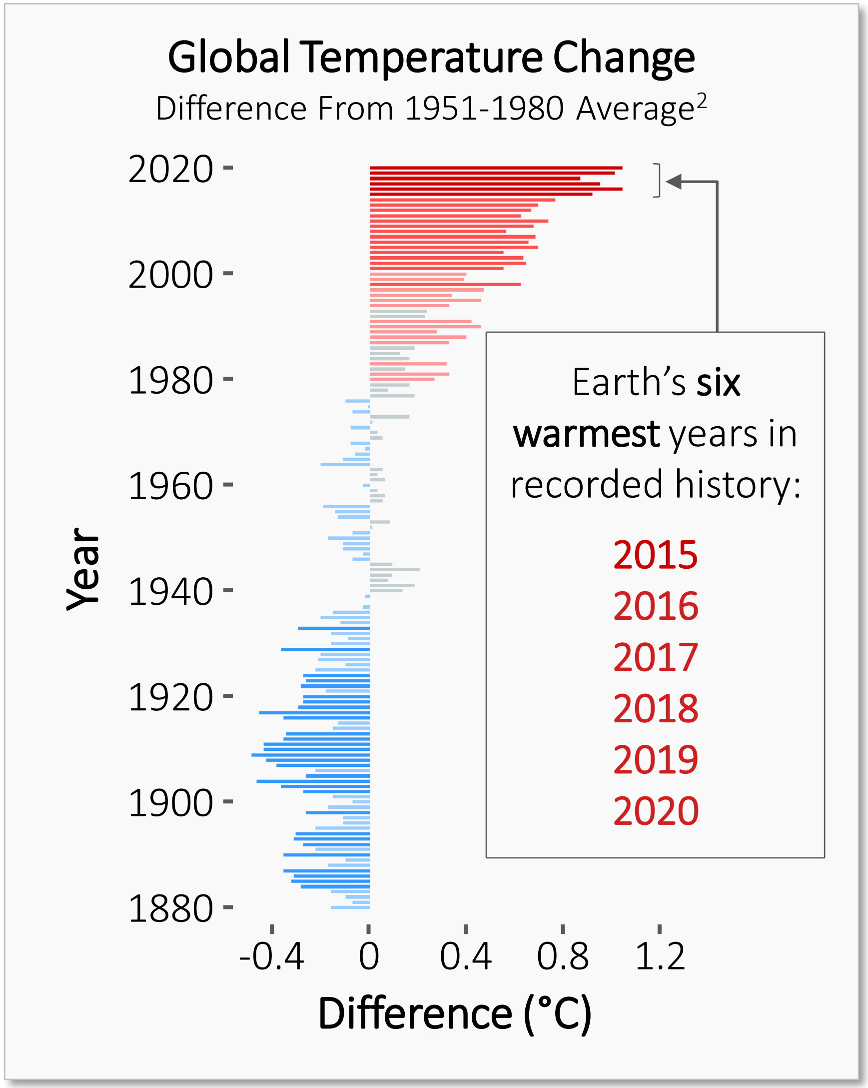
+25 ppm over 20 years

1960 **315 ppm**

Pre-Industrial **280 ppm**

+95 ppm natural emissions over 20,000 years

Last Ice Age **185 ppm**



Global Temperature Change

Difference From 1951-1980 Average[2]

Earth's **six warmest** years in recorded history:

2015
2016
2017
2018
2019
2020

Link for citations and additional notes

The Paris Accord, the most comprehensive international climate agreement in history, will not keep warming below 2°C even if all its current targets are met

Paris Accord
(In Theory)

- Signed in **2015** by **almost every country on Earth**
- "Binding" pledge to limit average global temperature rise to **1.5°C** to **2°C** above **pre-industrial temperatures**

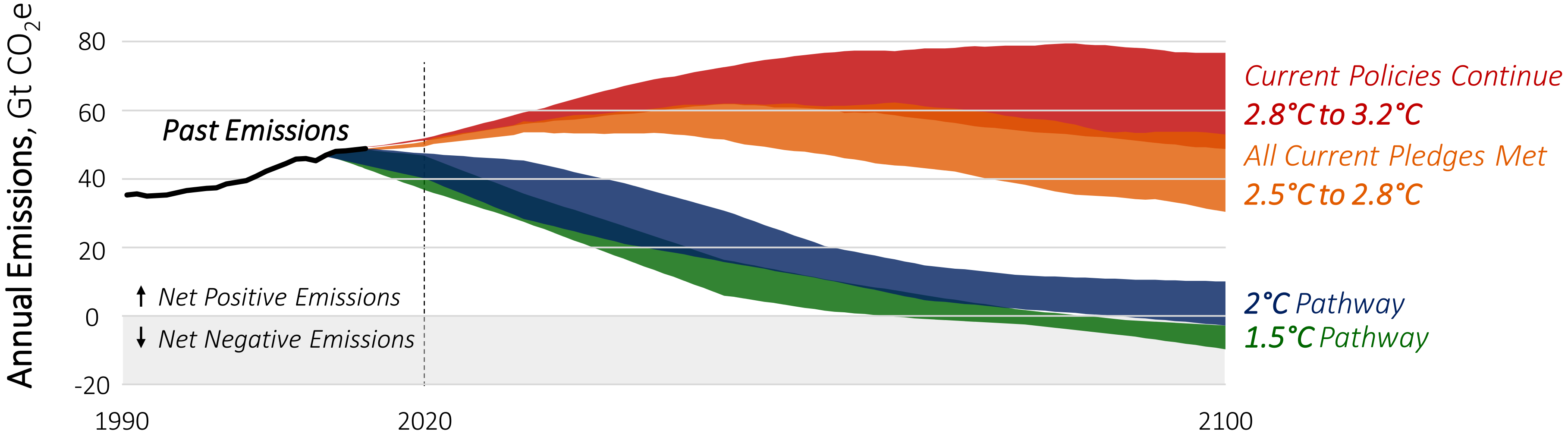
Paris Accord
(Optimistically)

- Despite pledge, **countries' plans for emissions cuts aren't enough** to hold us even to 2°C
- **Even if all current plans are fully met**, temperature is projected to **rise 2.5°C-2.8°C** by 2100

Where We're At Now

- Even worse, many signatories are **failing to meet** their **already insufficient** national plans
- If **current policies continue**, temperature is projected to rise **2.8°C-3.2°C** by 2100

Global Heating Pathways by 2100[1]



Relative to pre-industrial temperatures, +1.5°C=+2.7°F, +2°C=+3.6°F, +2.5°C=+4.5°F, +2.8°C=+5.0°F, +3.2°C=+5.8°F; link for citations and additional notes

This section explores the huge damage fossil fuels and climate change wreak today, and the threats they pose to our future

Key Argument

Fossil fuels unleash severe pollution and climate damage, **making Earth a more hostile home for human life**

Climate change adds fuel to extreme weather events and drives long-term ecosystem damage, reshaping Earth to be more hostile to humans

Climate change's weather effects can be broken into
fire and water

EXTREME WEATHER

- ***Heatwaves** are **fiercer** and **more frequent***
- ***Droughts** are **longer and more severe***

- *In warmer air, it **takes longer** for rain to build up, then **rains harder***
- *Warmer oceans **feed more energy** into **bigger, stronger hurricanes***

STEADY DAMAGE

- ***Disease-bearing** and **crop-eating** insects **thrive** and **expand territory***
- ***Growing seasons** are more erratic; higher CO_2 **reduces crop nutrients***

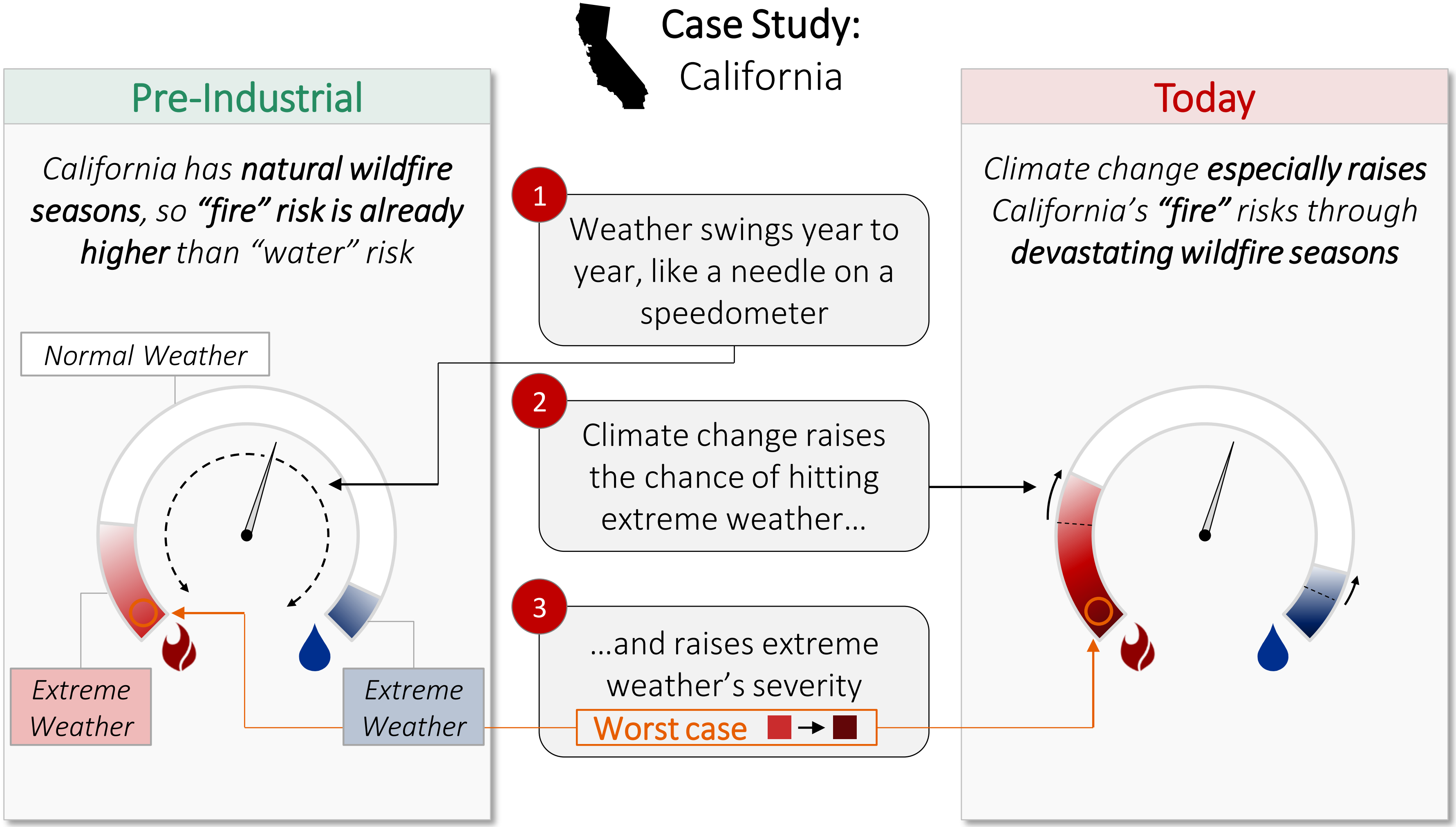
- *Melting ice and snow, and heat expansion of water, **raise sea level***
- *Ocean water is **hotter** and **more acidic,** threatening **marine life***

IMPACTS

- *Threats to human life*
- *Fiercer wildfire seasons*
- *More infectious disease*
- *Disruptions to agriculture*
- *Collapse of ocean ecosystems*
- *Destroyed freshwater sources*
- *Increased flooding*
- *Submerged coasts*

Link for citations and additional notes

We can visualize any region's weather as a speedometer, with rising global temperatures expanding the extreme zones and making them more severe



Case Study:
California

Pre-Industrial

*California has **natural wildfire seasons**, so **"fire" risk is already higher** than "water" risk*

Normal Weather

Extreme Weather

Extreme Weather

1 Weather swings year to year, like a needle on a speedometer

2 Climate change raises the chance of hitting extreme weather…

3 …and raises extreme weather's severity

Worst case ■ → ■

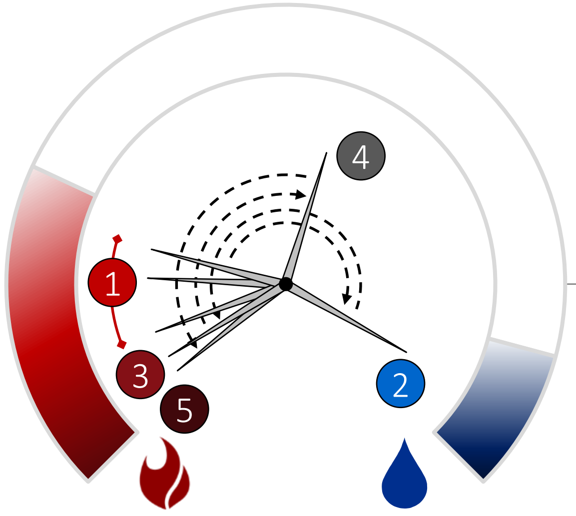
Today

*Climate change **especially raises** California's **"fire"** risks through **devastating wildfire seasons***

Note that these charts are a visualization tool – the actual number values are hypothetical. Link for citations and additional notes

California's 2010s gave a terrible forecast of the damage that more volatile and severe extreme weather can do, even in the world's wealthiest country

California, 2011-2020



① *2011-17*	***Brutal drought set stage for devastating wildfire seasons****; 9 of CA's 10 largest fires on record have been since 2012, and top 7 since 2017*[1]
② *2016-17*	***Severe rainfall nearly broke CA's 2nd largest reservoir****, which would have unleashed massive floods; 180,000 people evacuated*[2]
③ *2018*	*CA's* ***most destructive fire season in recorded history, with 2M acres burned, 100 people killed;***[3] *cost estimates range from $24B to $350B*[4]
④ *2019*	*Moderate weather, only 0.3M acres burned*[5]
⑤ *2020*	*CA had over* ***4M acres burned,***[6] ***shattering the 2018 record for its largest fire season*** *in modern history*

Link for citations and additional notes, including analysis of human activity aside from climate change that has also contributed to CA's increasingly severe wildfire seasons

It's hard to prove exactly how much climate change accelerates any specific weather event, but the evidence of escalating extreme weather is irrefutable

Extreme weather has happened naturally throughout human history, so ***how can we be sure that recent extreme events really are accelerated by climate change?***

Event attribution is rapidly improving[1]

A 2018 heatwave in Japan caused 1,000+ deaths and was assessed as ***impossible without human-caused climate change***[2]

Conditions for Australia's catastrophic 2019 wildfires are now ***at least 30% more likely than without human-caused climate change***[3]

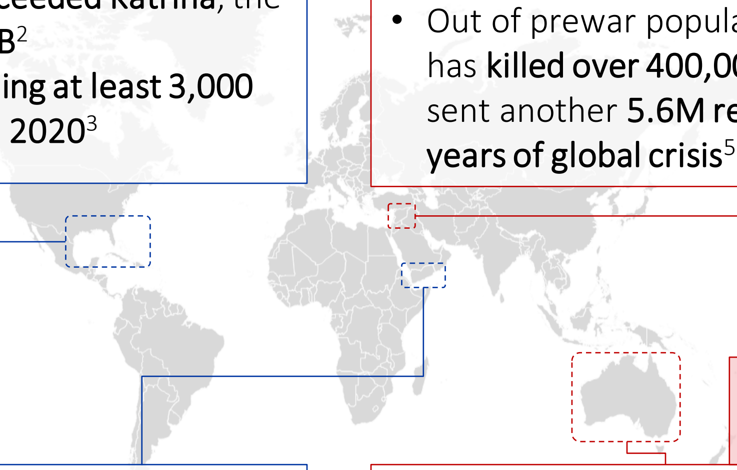
A fierce 2020 heatwave and wildfire season in Russia was ***assessed as "nearly impossible" without human-caused climate change***[4]

Overall trends are clear

Scientific evidence confirms that ***climate change worsens the natural conditions that cause extreme weather***[5]

Link for citations and additional notes

Extreme weather can shake the world's wealthiest nations or tilt already-struggling countries into chaos, setting off global crises



Southeast U.S., 2017

- **Back-to-back Harvey, Maria, and Irma** were the **2nd, 3rd**, and **5th costliest hurricanes in U.S. history**[1]
- Combined costs of **over $250B exceeded Katrina**, the worst U.S. hurricane ever, by **$35B**[2]
- Maria devastated Puerto Rico, **killing at least 3,000 people**; recovery is **still ongoing** in **2020**[3]

Syria, 2006-2011

- Syria's **worst drought** in **recorded history** destroyed farming, **wrecking economy** and **food supply,** and helped spark the 2011 **eruption of civil war**[4]
- Out of prewar population of 22M, the ongoing war has **killed over 400,000,** internally displaced **6.2M,** sent another **5.6M refugees abroad**, and driven **years of global crisis**[5]

Yemen, 2015

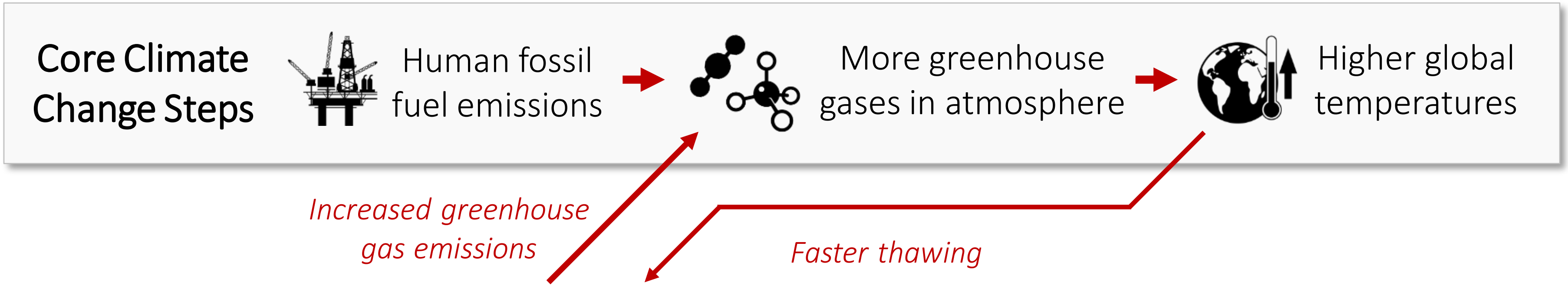
- **Two cyclones**, one the **first hurricane-strength storm** to hit Yemen in **recorded history**, hit **within 10 days**[6]
- Heavy rains fueled **locust infestation** that **devastated crops,**[7] **deepening famine**
- Worsened **ongoing civil war** and **UN-declared worst humanitarian crisis on Earth**, with **24M people** – 80% of Yemen's population **– in need of aid**[8]

Australia, 2017-2019

- **Drought** began in 2017 and led up to 2019, the **driest spring** and **hottest year in Australia's history**, setting off **catastrophic wildfire season**[9]
- Fires burned a **land area the size of England**, killed **hundreds of people,** killed or displaced 3B animals, and **sent clouds of smoke around the entire planet**[10]

Link for citations and additional notes

Rising temperatures fuel natural processes that lead to further heating, creating vicious cycles that could send climate change spiraling out of control



Core Climate Change Steps

Human fossil fuel emissions → More greenhouse gases in atmosphere → Higher global temperatures

Increased greenhouse gas emissions

Faster thawing

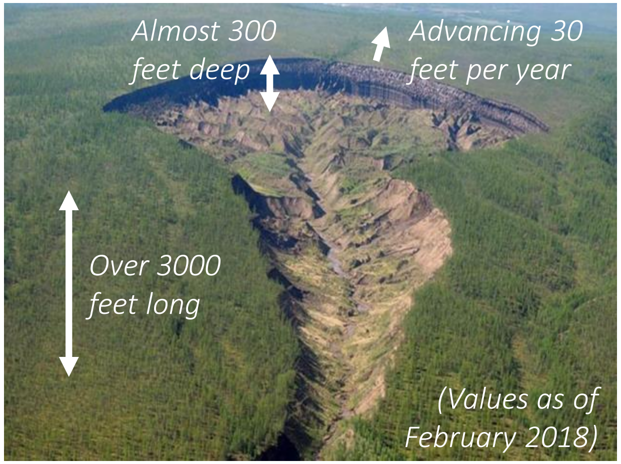
Thawing Permafrost

Year-round frozen soil** called **permafrost** spans **6B acres** in Earth's north, covering **buried remains of ancient grasslands

*Permafrost **locks away 1,600 Gt of carbon** – about twice as much as is in the **entire atmosphere today***

*As rising temperatures melt permafrost, it **releases huge reserves** of greenhouse gases **CO_2** and **methane**[2]*

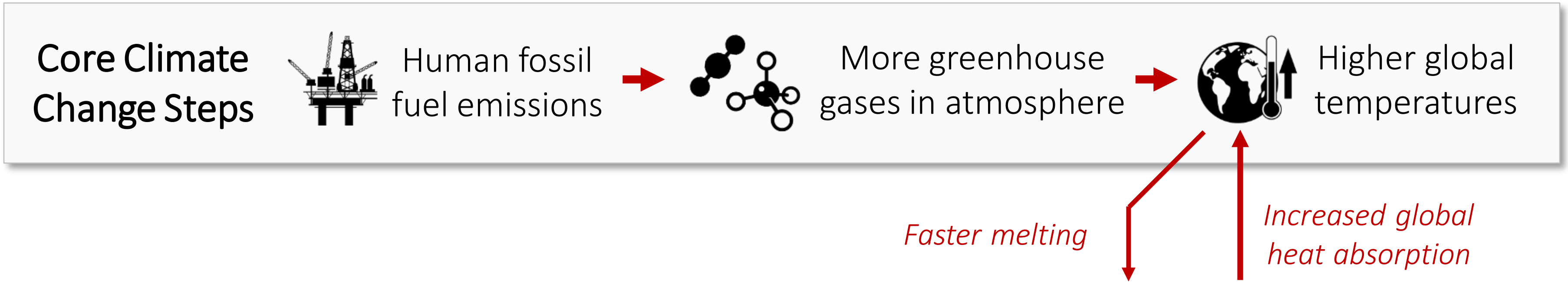
Collapsed permafrost in Russia[1]



*Permafrost emits **0.3-0.6 Gt of carbon per year,**[3] roughly **as much as Australia,**[4] plus methane, an even stronger greenhouse gas;[5] **the more Earth warms, the faster this accelerates**, driving **even more warming***

Link for citations and additional notes

Rising temperatures fuel natural processes that lead to further heating, creating vicious cycles that could send climate change spiraling out of control



Core Climate Change Steps

Human fossil fuel emissions → More greenhouse gases in atmosphere → Higher global temperatures

Faster melting

Increased global heat absorption

North Pole satellite image[1]

Melting Sea Ice

*As Earth has warmed, Arctic summer ice has **shrunk 13% per decade** since 1979,[2] and may be entirely gone by 2035[3]*

*Bright snow-covered ice **reflects 90%** of sunlight and **absorbs 10%** as heat; dark seawater **reflects 6%** and **absorbs 94%**[4]*

*The more ice melts into the ocean, the **more heat the water absorbs**, **melting even more ice** and further heating Earth*

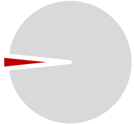
*Research suggests that **increased warming** driven by melted ice has **added about 25% as much heating as the rise in atmospheric CO_2**, seriously **accelerating global warming** and **driving further melting**[5]*

Link for citations and additional notes

Even leaving climate change aside, fossil fuels cause devastating global human and economic damage through air pollution

$2.9 trillion

Annual global economic damage of air pollution, equal to 3.3% of global GDP[1]



Premature Death

Air pollution is the **world's 4th leading risk factor for death**, **linked to 5M deaths** in 2017, with huge human and labor force costs

Lost Work Hours

Even non-lethal air pollution health effects can undermine productivity; **air pollution drives 1.8B days of work absence** per year

Healthcare Costs

Air pollution imposes huge health burdens on societies, including **4M new child asthma cases**, **2M pre-term births**, and chronic sickness

National Annual Air Pollution Costs[2]

	**China**	**$900B** (**6.6%** of GDP) **1.8M** premature deaths
	**India**	**$150B** (**5.4%** of GDP) **1M** premature deaths
	**U.S.**	**$600B** (**3.0%** of GDP) **230,000** premature deaths

The U.S. alone could save $37T in 2020-2070 pollution and climate impact costs, or $700B/year,[3] if the world adopts enough clean energy to limit warming to 2°C

Relative to pre-industrial temperatures, +2°C=+3.6°F; link for citations and additional notes

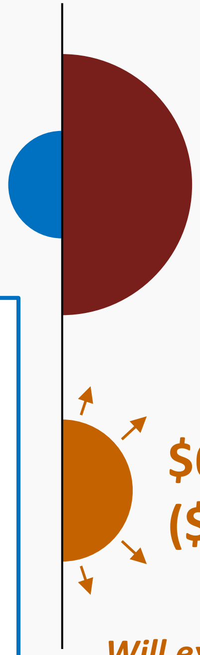
Moving beyond fossil fuels will require huge investment, but will be vastly cheaper than continuing to endure their side effects

Additional Investment Needed

To limit warming to 2°C

The Price We're Paying

For continuing to depend on fossil fuels



$15T 2020-2050[1]
($500B per year)

- Plan adds **$15T to $95T in already-expected** energy investment by 2050, with increased focus on clean tech
- Each **$1 invested** is expected to bring **$3-$7** savings in **reduced pollution costs** and **cut fossil fuel subsidies**[1]

$2.9T per year[2]

Estimated **global economic costs** from fossil fuel **air pollution**

$69T 2020-2100[3]
($863B per year)

Projected 2020-2100 climate change damages even **if we only warm by 2°C**

Will expand if we keep pace to warm over 2°C

The **faster we develop a renewable economy, the more we will save** in the long run by reducing the **crippling human and economic damage of air pollution and climate change**

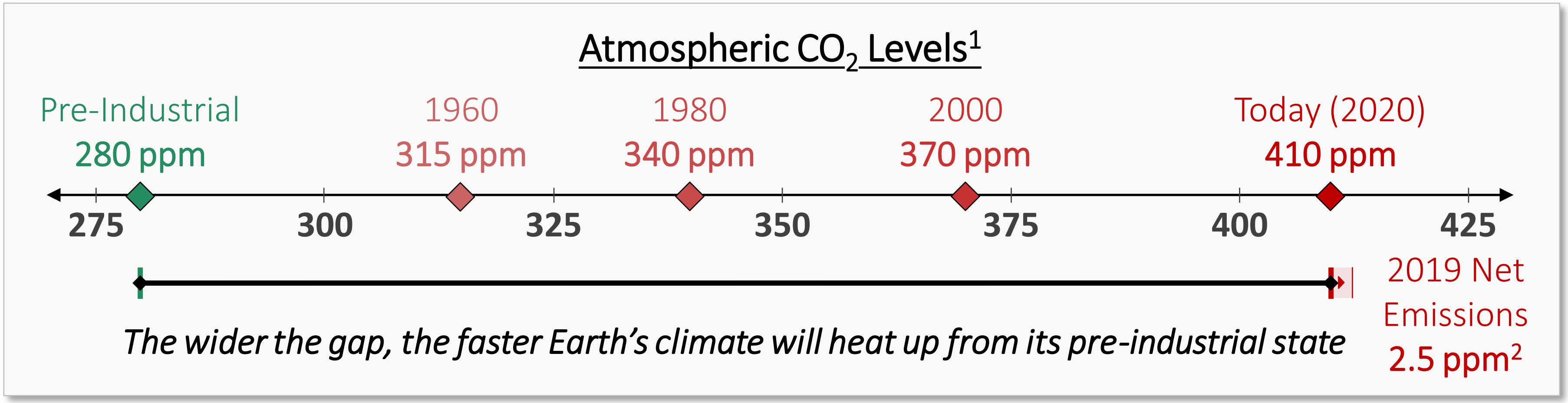
Relative to pre-industrial temperatures, +2°C=+3.6°F; link for citations and additional notes

This section explores the technologies we can use to cut our dependence on fossil fuels and to slow, halt, and then reverse climate change

Key Argument

Clean technology is being rapidly developed and deployed, but **needs to accelerate even faster** to meet the threat of climate change

The speed of climate change is determined by total CO_2 in the atmosphere, so cutting new emissions is only the beginning of our path to recovery



Atmospheric CO_2 Levels[1]

The wider the gap, the faster Earth's climate will heat up from its pre-industrial state

Steps to Restoring a Stable Climate

Cut Emissions → **CO_2 Removal** → **Emergency Brake**

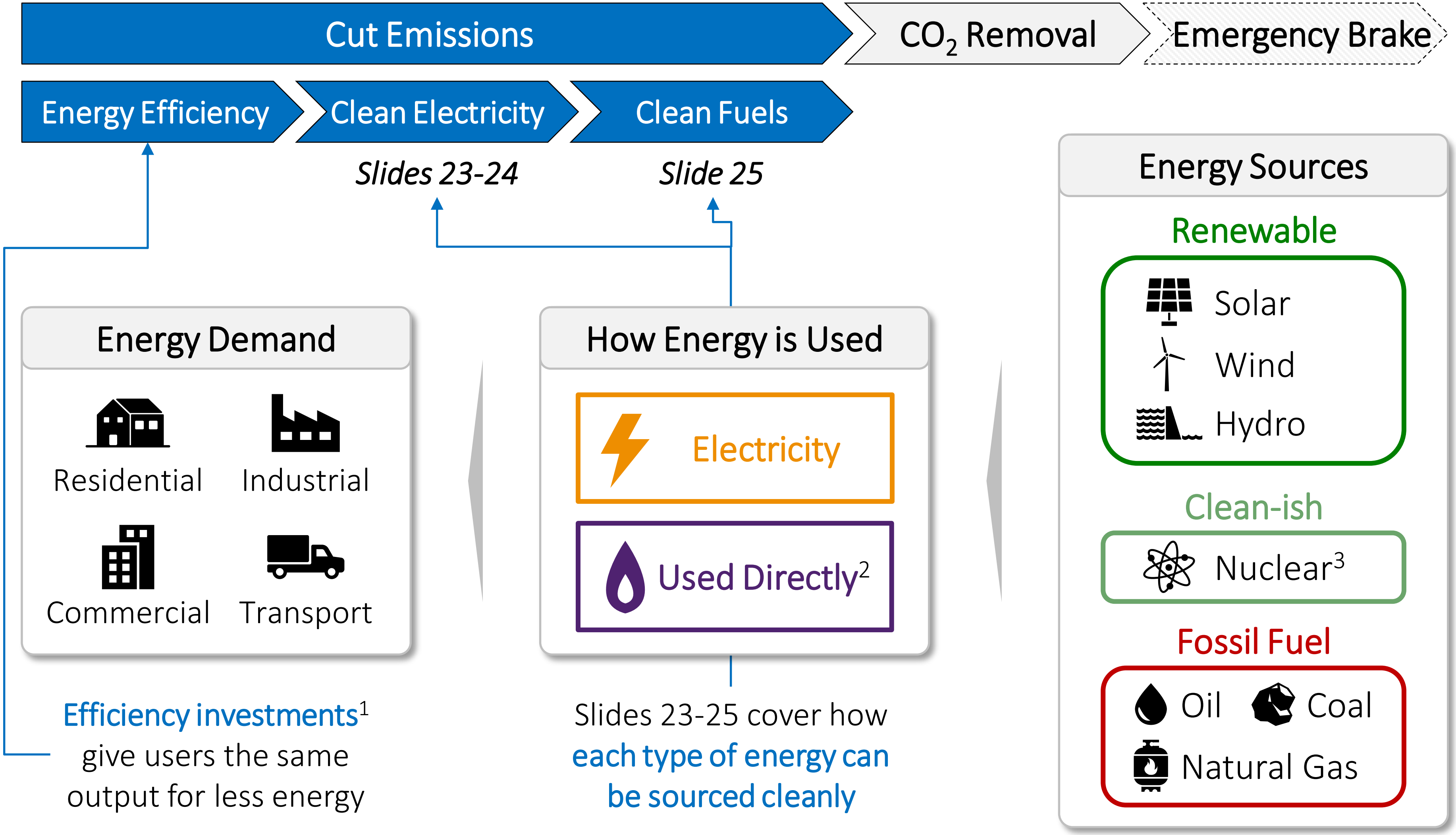
Adopt clean technology to **power civilization while producing less and less CO_2**

Extract carbon from the atmosphere and store it permanently

Research last-resort options that could **slow warming to buy more time**

Link for citations and additional notes; "Net Emissions" is the total added to the atmosphere, taking account of human emissions minus the extra amount currently absorbed by Earth's land and oceans

We can cut emissions by sourcing electricity and other energy from clean sources, and by using their power more efficiently



Cut Emissions > CO_2 Removal > Emergency Brake

Energy Efficiency > Clean Electricity > Clean Fuels

Slides 23-24 *Slide 25*

Energy Demand

- Residential
- Industrial
- Commercial
- Transport

How Energy is Used

- Electricity
- Used Directly[2]

Energy Sources

Renewable

- Solar
- Wind
- Hydro

Clean-ish

- Nuclear[3]

Fossil Fuel

- Oil
- Coal
- Natural Gas

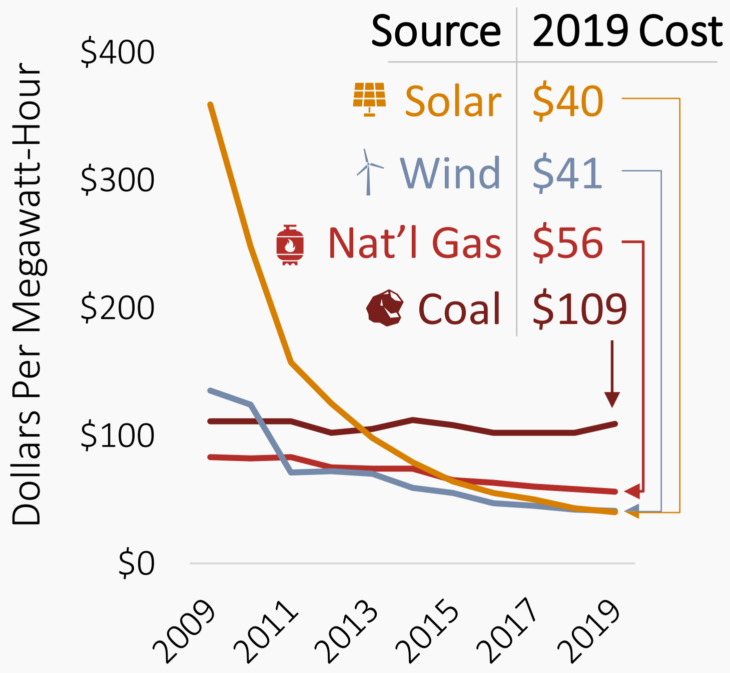
Efficiency investments[1] give users the same output for less energy

Slides 23-25 cover how **each type of energy can be sourced cleanly**

Link for citations and additional notes, and link to see a version of chart with 2019 U.S. numbers at each stage. Only shows the top global energy sources (e.g., excludes geothermal and biomass)

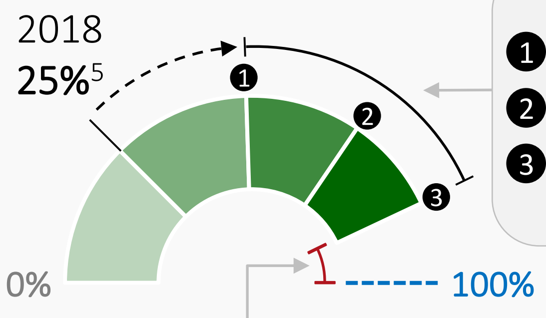
Renewable electricity is surging due to cost-slashing innovation, but not fast enough to fully take over global power grids for decades

Electricity Generation Levelized Cost[1]



Source	2019 Cost
Solar	$40
Wind	$41
Nat'l Gas	$56
Coal	$109

Global Renewable[2] Share of Electricity Generation



2050 Forecasts

- ① *U.S. EIA[3]* 49%
- ② *Bloomberg NEO[4]* 69%
- ③ *IRENA 2°C Plan[5]* 86%

↑ *Requires More Investment*

Even in an **optimistic case with more investment in renewables**, the world will still **rely on non-renewable electricity sources by 2050**

Relative to pre-industrial temperatures, +2°C=+3.6°F; link for citations and additional notes, and link for energy share analysis of the world's top 8 electricity producing countries

Power grids can't fully rely on renewable electricity or maximize its efficiency until energy storage and transmission challenges are overcome

Storage Challenges

Sunlight and wind are intermittent and **vary widely over days, weeks, and seasons**

Current grid-scale battery technology can **only store up to about six hours of power**[1]

As a result, most areas need **non-renewable power available** to guarantee supply

Emerging Solutions

A huge range of **new energy storage solutions**[2] are in development

Extra renewable energy can be used to **manufacture clean fuels** →

Transmission Challenges

The **best renewable energy sites are often remote**, like deserts, plains, and offshore

These areas are usually **far from cities and factories** where most power is consumed

Many countries lack enough **long-distance power lines** to connect supply to demand[3]

Emerging Solutions

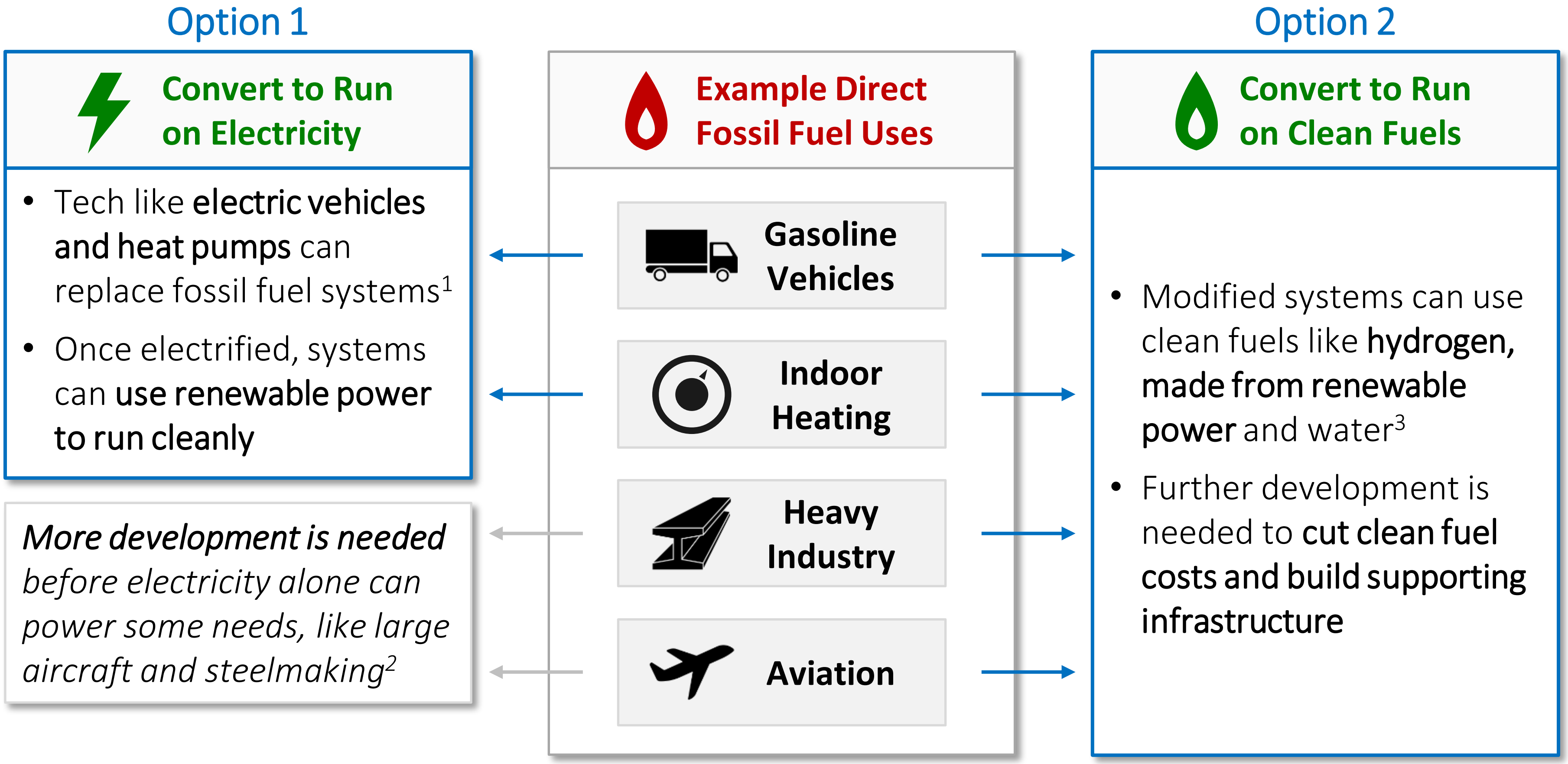
Long-distance power lines **need more investment and support**[4]

Clean fuels can be **made at renewable generation sites and sent to consumers**[5]

Electricity grids will require some non-renewable baseload power until these challenges are overcome

Link for citations and additional notes

Activity that currently depends on directly burning fossil fuels can be converted to run on renewable-sourced electricity or on clean fuels



Option 1

Convert to Run on Electricity

- Tech like **electric vehicles and heat pumps** can replace fossil fuel systems[1]
- Once electrified, systems can **use renewable power to run cleanly**

More development is needed *before electricity alone can power some needs, like large aircraft and steelmaking*[2]

Example Direct Fossil Fuel Uses

- **Gasoline Vehicles**
- **Indoor Heating**
- **Heavy Industry**
- **Aviation**

Option 2

Convert to Run on Clean Fuels

- Modified systems can use clean fuels like **hydrogen, made from renewable power** and water[3]
- Further development is needed to **cut clean fuel costs and build supporting infrastructure**

Link for citations and additional notes

Returning our atmosphere to pre-industrial CO_2 levels will require massive global carbon capture and storage using methods that are still in development

Cut Emissions > CO_2 Removal > Emergency Brake

Energy Efficiency > Clean Electricity > Clean Fuels > Carbon Capture

Major proposed technologies[1]	Expected Cost per ppm	Maximum Withdrawal Rate
Global Forestation Planting new forests absorbs carbon in trees and soil	$10B-$100B	-1.7 ppm/year $17B to $170B
Bioenergy Carbon Capture and Storage Burning crops in sealed chambers can generate power while capturing carbon	$215B-$425B	-2.4 ppm/year $500B to $1T
Direct Air Capture DAC plants draw CO_2 directly from atmosphere using chemical reactions	$215B-$640B	-18.8 ppm/year $4T to $12T

← The CO_2 gap is **130 ppm** and growing[2] →

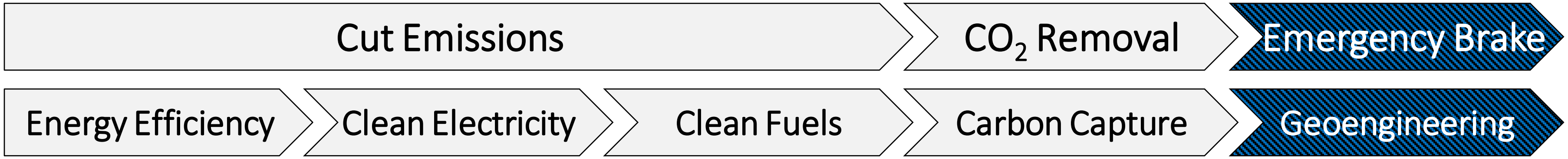
Pre-Industrial **280 ppm**

2020 **410 ppm**

Net Emissions **+2.5 ppm/year**[3]

Link for citations and additional notes; "Net Emissions" is the total added to the atmosphere, taking account of human emissions minus the extra amount currently absorbed by Earth's land and oceans

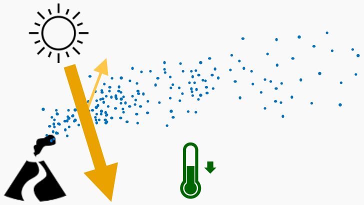
If we can't build a sustainable economy fast enough to avert catastrophic damage, solar geoengineering could buy us emergency time



Cut Emissions > CO_2 Removal > **Emergency Brake**

Energy Efficiency > Clean Electricity > Clean Fuels > Carbon Capture > **Geoengineering**

Natural Inspiration[1]



① Eruption ⬆

Major volcanic eruptions shoot sulfur compounds high into upper atmosphere[1]

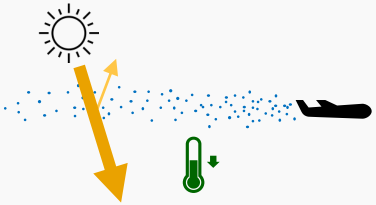
② Dispersal

Sulfur compounds float around globe and reflect small portion of sunlight, cooling Earth[1]

③ Return ⬇

Sulfur compounds fall back to Earth's surface over a couple of years

Solar Geoengineering



① Injection ⬆

Use high-flying aircraft to release reflective particles in the upper atmosphere

② Dispersal

Same as naturally

③ Return ⬇

Same as naturally

Solar geoengineering could ***stall warming*** *to* ***buy us more time*** *for* ***building a global renewable economy***

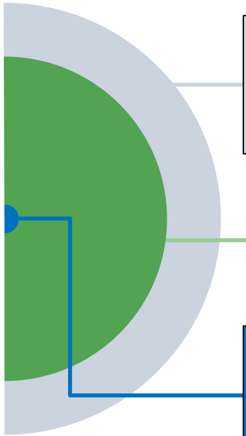
Global temperature change of -0.6°C=-1.1°F; link for citations and additional notes

Solar geoengineering could slash the pace of warming at a fraction of the investment needed to rapidly develop a global sustainable economy

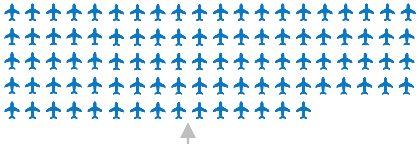
Cut Emissions > CO_2 Removal > **Emergency Brake**

Energy Efficiency > Clean Electricity > Clean Fuels > Carbon Capture > **Geoengineering**

Annual Spending (US Dollars)



$500B	Estimated[1] new clean energy investment, on top of reallocating planned energy investments, **needed every year** through 2050 to limit warming to 2°C
$282B	**Actual global investment** in new clean energy in 2019[2]
$2.3B	Annual cost estimate for geoengineering aircraft fleet to **cut the rate of further global warming in half** starting in 2033[3]



*95 aircraft needed over **first 15 years***

*For comparison, **FedEx had 679 aircraft** in 2020*[4]

Benefits

Fast, cheap, nature-proven method to **reduce symptoms of climate change**

Solvable Issues

May have environmental impacts, but tweaks to methods could avoid these[5]

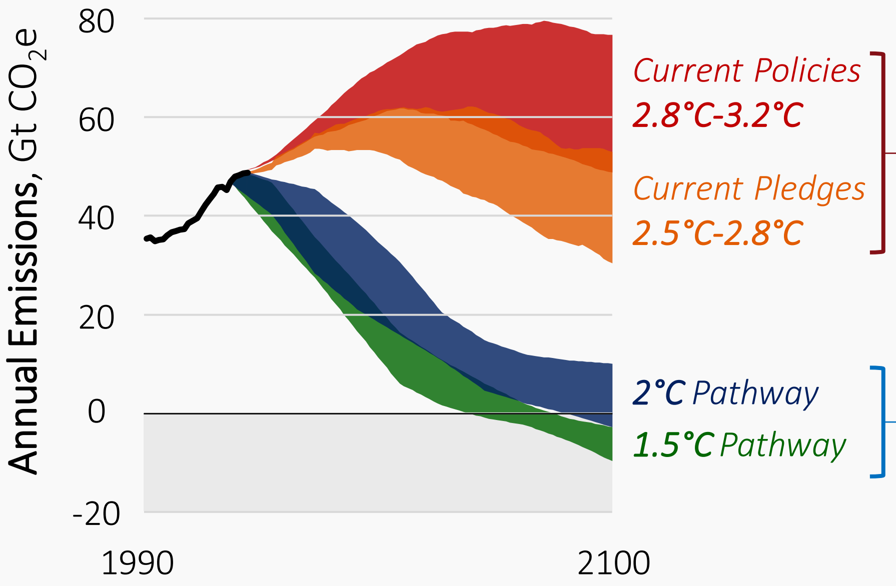
Challenges

Reducing threat of climate change may **reduce incentive to invest in solving its root causes**[6]

Relative to pre-industrial temperatures, +2°C=+3.6°F; link for citations and additional notes

Clean energy can drive far more long-term growth and prosperity than fossil fuels, and we have a clear roadmap of technology to develop and deploy

Global Heating Pathways by 2100[1]



Our Choice[2]

Dependence

Short-term savings but massive long-term pollution and climate change costs, and money wasted maintaining fossil fuel infrastructure

Freedom

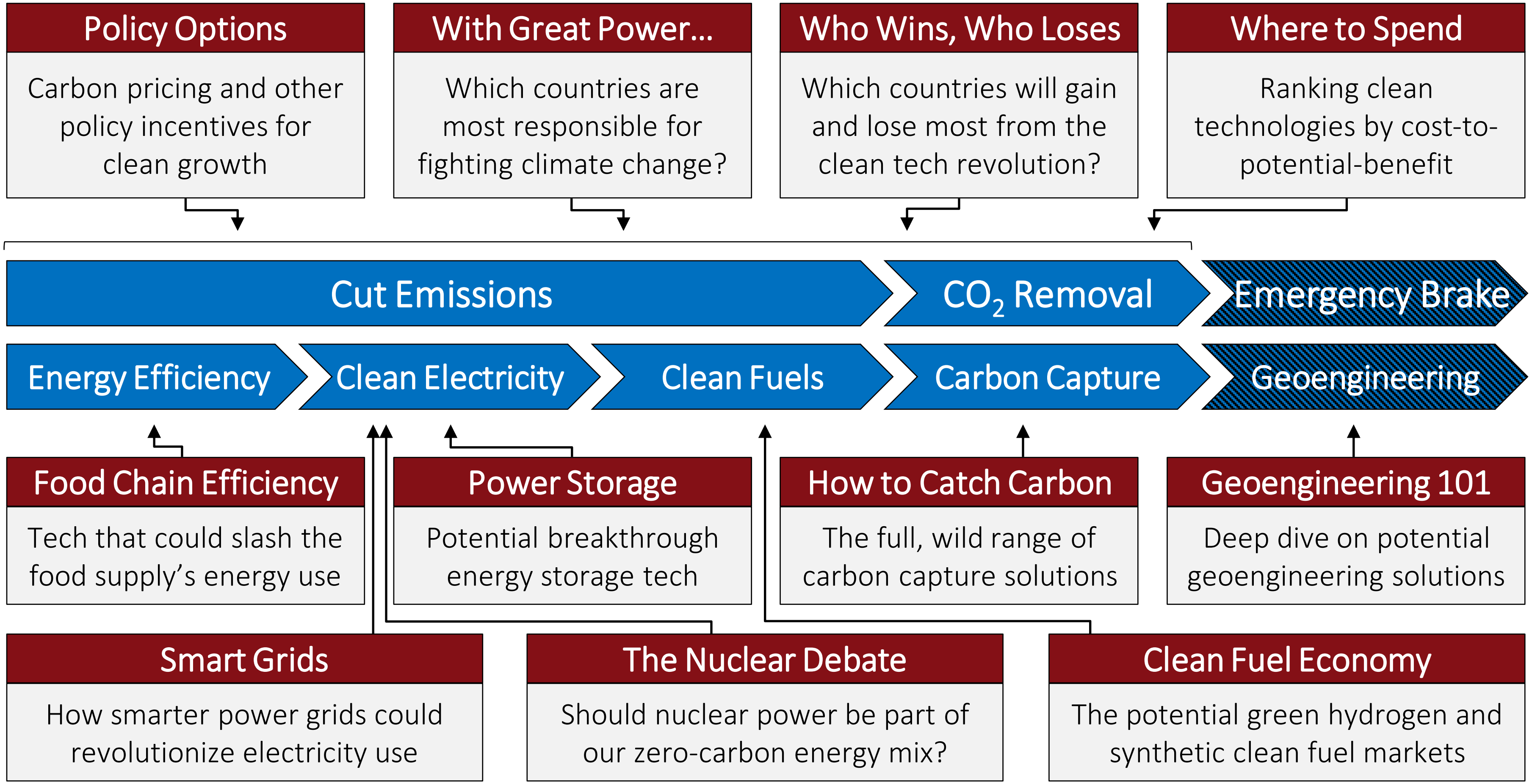
Investment buys clean growth, huge savings from avoided damages, and a path to a stable Earth that protects humanity's future

Our Technology Roadmap

- Cut Emissions
  - Energy Efficiency
  - Clean Electricity
  - Clean Fuels
- CO_2 Removal
  - Carbon Capture
- Emergency Brake
  - Geoengineering

Pathway temperatures are by 2100, relative to pre-industrial temperatures; +1.5°C=+2.7°F, +2°C=+3.6°F, +2.5°C=+4.5°F, +2.8°C=+5.0°F, +3.2°C=+5.8°F; link for citations and additional notes

As a primer on how climate change works and how we can solve it, this piece sets a foundation for a wide range of potential follow-up research



Policy Options

Carbon pricing and other policy incentives for clean growth

With Great Power…

Which countries are most responsible for fighting climate change?

Who Wins, Who Loses

Which countries will gain and lose most from the clean tech revolution?

Where to Spend

Ranking clean technologies by cost-to-potential-benefit

Cut Emissions

CO_2 Removal

Emergency Brake

Energy Efficiency

Clean Electricity

Clean Fuels

Carbon Capture

Geoengineering

Food Chain Efficiency

Tech that could slash the food supply’s energy use

Power Storage

Potential breakthrough energy storage tech

How to Catch Carbon

The full, wild range of carbon capture solutions

Geoengineering 101

Deep dive on potential geoengineering solutions

Smart Grids

How smarter power grids could revolutionize electricity use

The Nuclear Debate

Should nuclear power be part of our zero-carbon energy mix?

Clean Fuel Economy

The potential green hydrogen and synthetic clean fuel markets

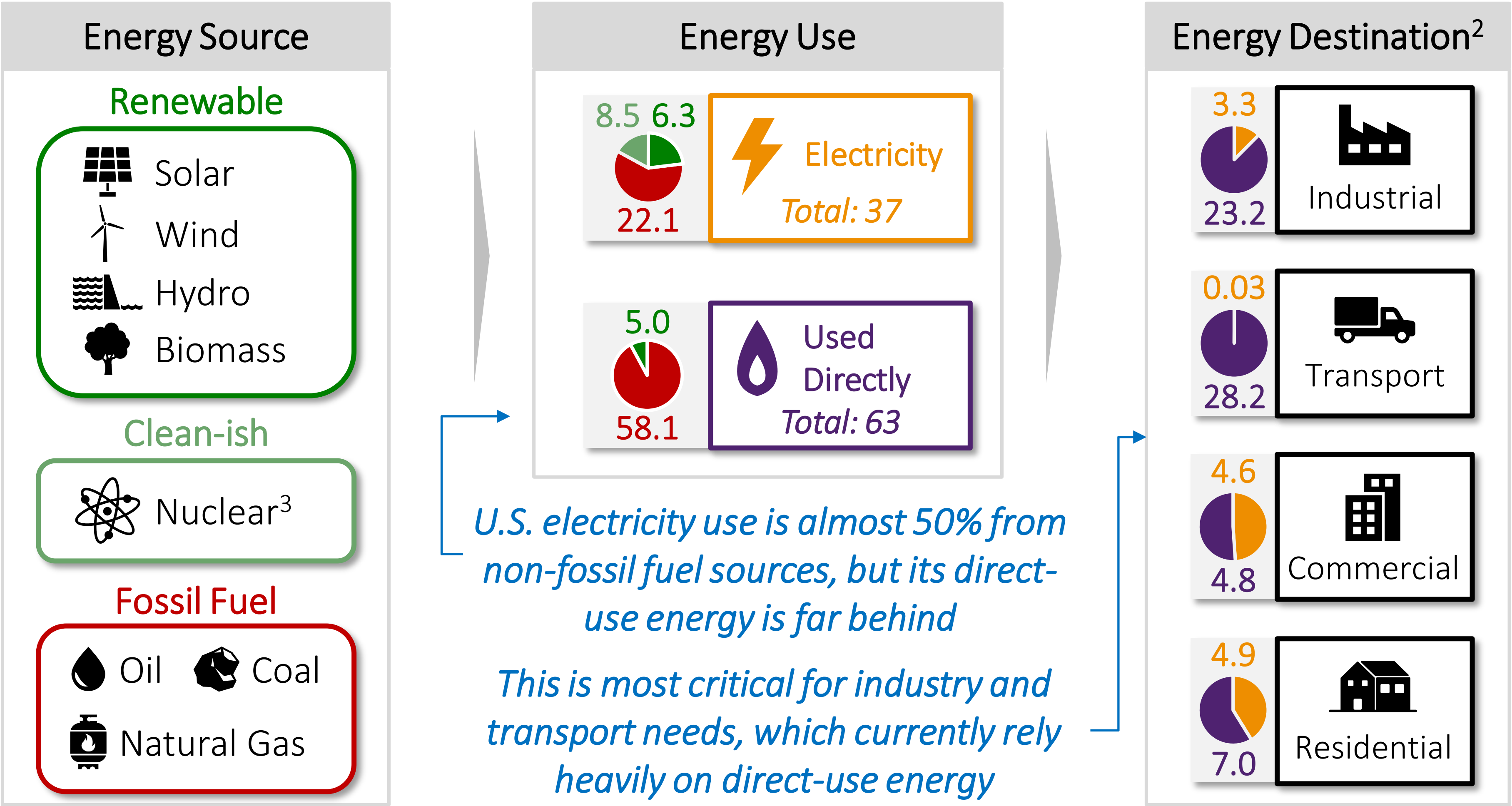
This is a small sample of the many questions we need to investigate, and answer, to free ourselves from fossil fuels and restore a stable climate

Link to return to conclusion slide

This is a walkthrough of the slide 22 "Energy Picture" chart, using 2019 U.S. numbers, to give a sense for the scale of the decarbonization challenge we face

2019 U.S. Energy Production and Consumption[1]

(In quadrillion British Thermal Units)



Energy Source

Renewable

- Solar
- Wind
- Hydro
- Biomass

Clean-ish

- Nuclear[3]

Fossil Fuel

- Oil
- Coal
- Natural Gas

Energy Use

8.5 6.3 22.1	Electricity *Total: 37*
5.0 58.1	Used Directly *Total: 63*

Energy Destination[2]

3.3 23.2	Industrial
0.03 28.2	Transport
4.6 4.8	Commercial
4.9 7.0	Residential

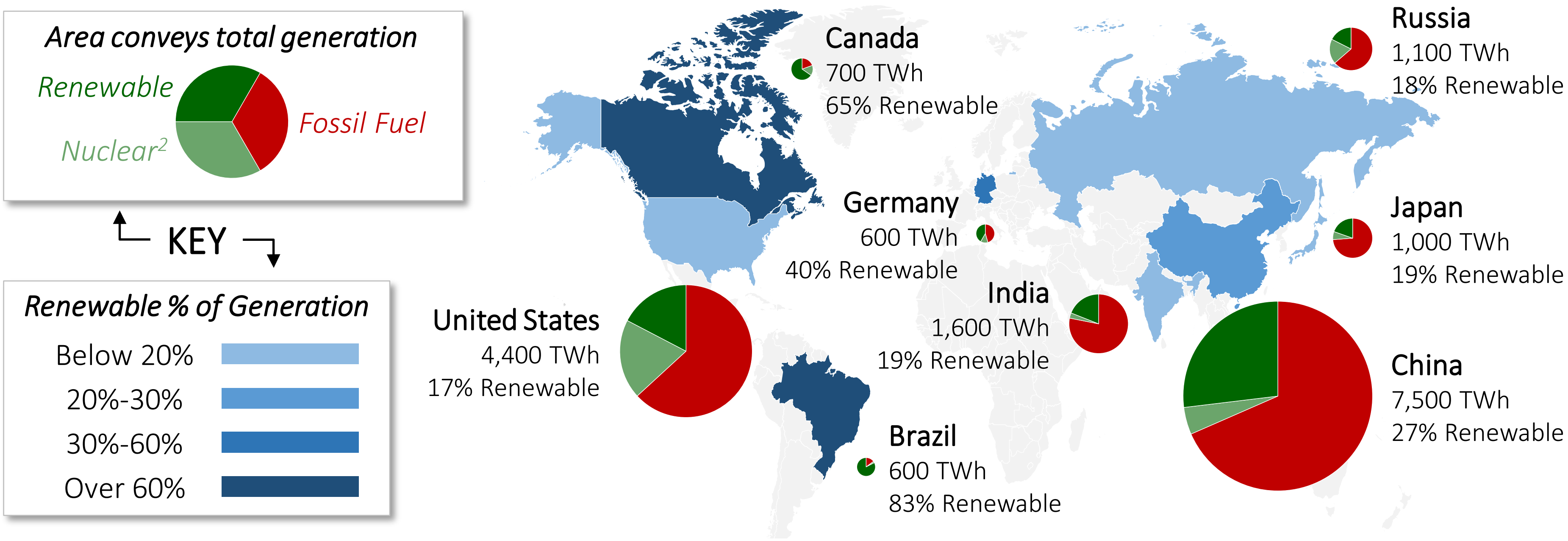
U.S. electricity use is almost 50% from non-fossil fuel sources, but its direct-use energy is far behind

This is most critical for industry and transport needs, which currently rely heavily on direct-use energy

Link for citations and additional notes, and link to return to slide 22. Only shows the top global energy sources (e.g., excludes geothermal and biomass)

The vast majority of countries still get most of their electricity from fossil fuels; even countries investing heavily in renewables are only slowly turning the tide

2019 Electricity Generation – Top 8 Power Consuming Countries[1]



Key Country Types

Hydro Lottery Winners

Countries with **geography** to mostly use **hydropower**, which has been a mature technology for decades

Small number of lucky countries

Examples: **Canada**, **Brazil**

Clean Investors

Countries **investing in renewables** and trying to **phase out fossil fuels** – at **widely varying speeds**

Most developed countries

Examples: **Germany**, **U.S.**

All The Above

Developing countries **expanding both renewables and fossil fuels** to meet **fast-rising energy demand**

Most developing countries

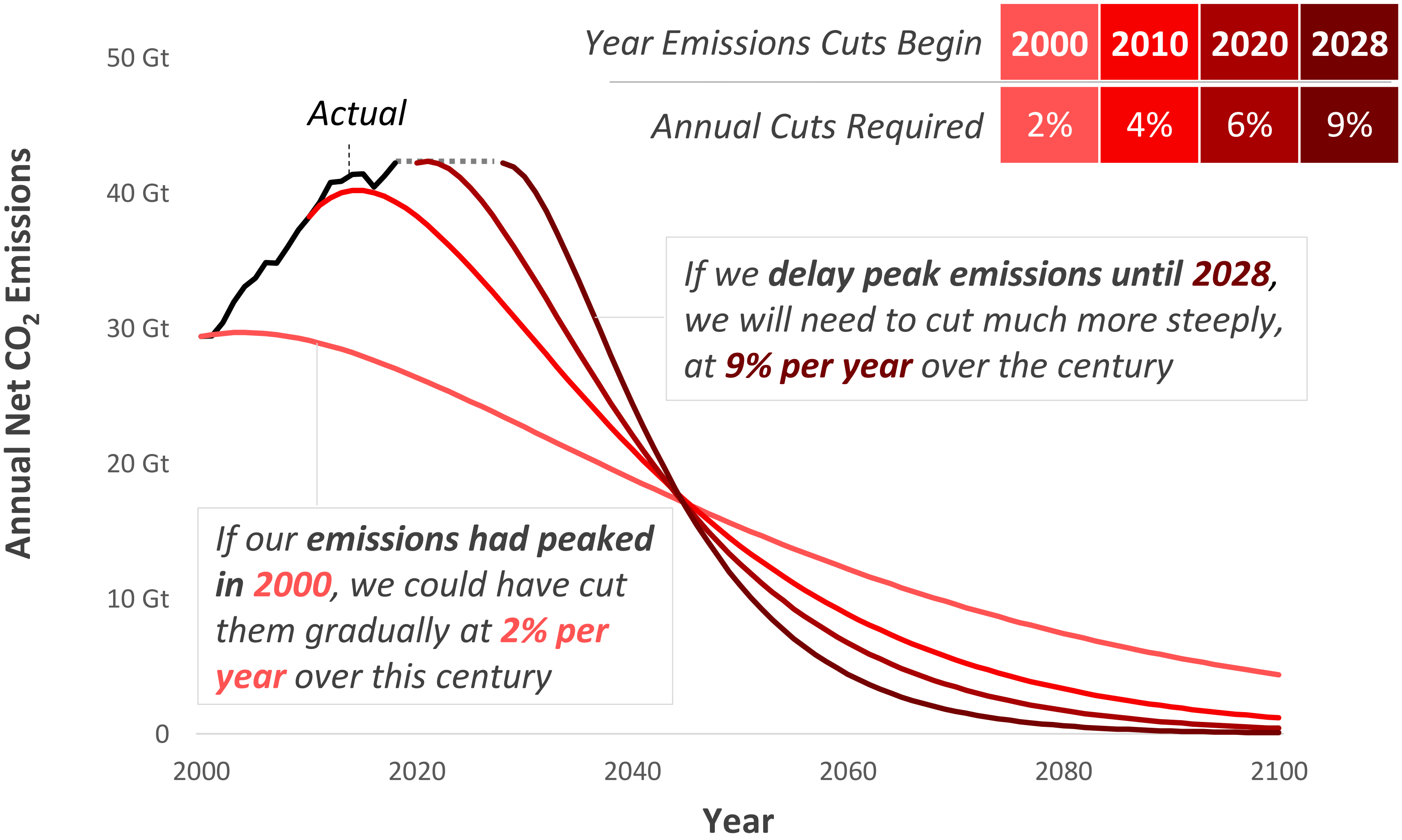
Examples: **China**, **India**

Link for citations and additional notes, and link to return to slide 23, which references this slide

APPENDIX: THE COSTS OF DELAY

The longer we delay cutting emissions, the harder it will be to return to a 2°C pathway, until dangerous levels of temperature rise are impossible to avoid

Global CO_2 Emissions Pathways to Stay Below 2°C Average Temperature Rise[1]



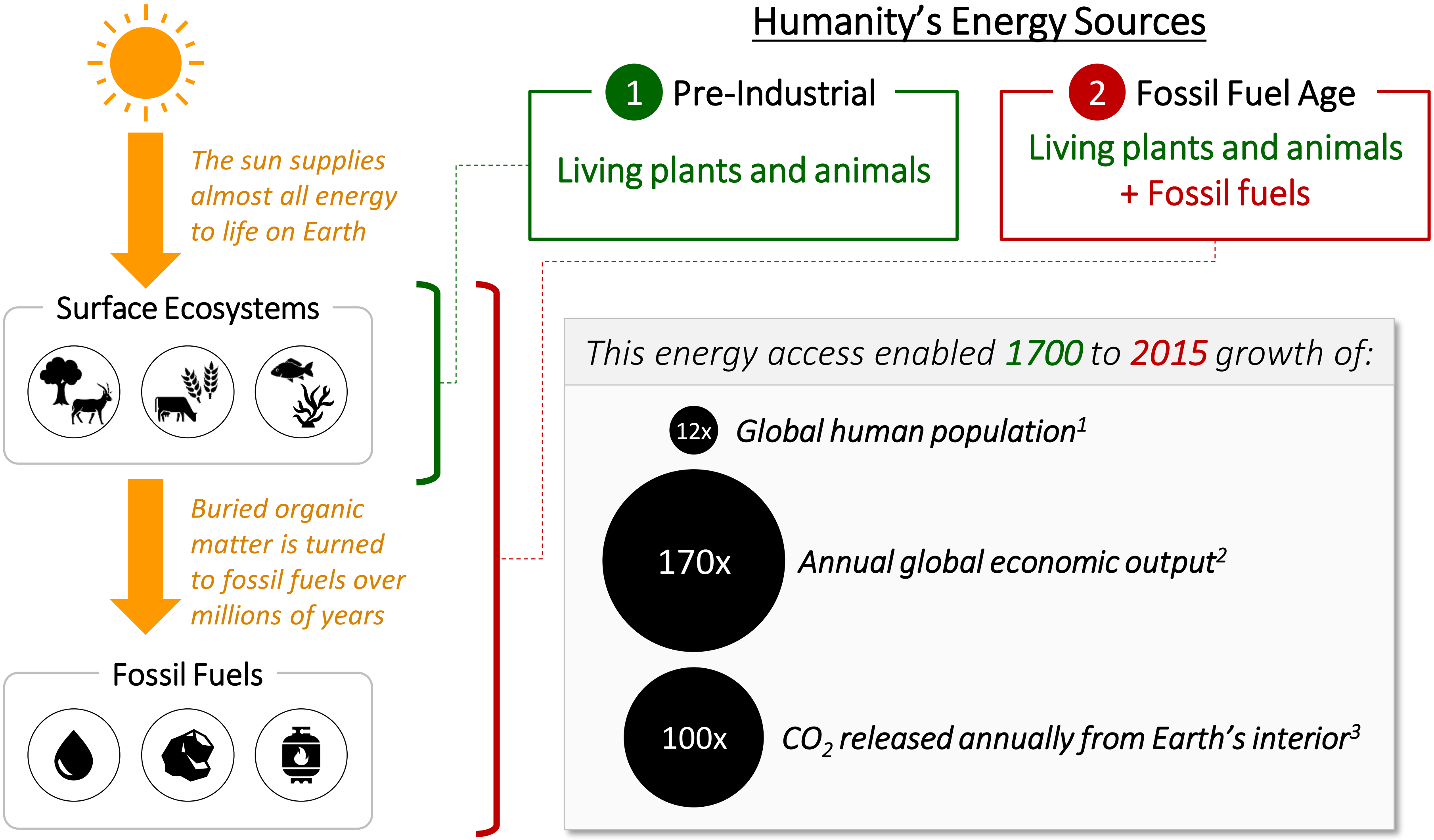
Year Emissions Cuts Begin	2000	2010	2020	2028
Annual Cuts Required	2%	4%	6%	9%

*If we **delay peak emissions until 2028**, we will need to cut much more steeply, at **9% per year** over the century*

*If our **emissions had peaked in 2000**, we could have cut them gradually at **2% per year** over this century*

Link for citations and additional notes

By burning fossil fuels we've unleashed millions of years of stored energy and CO_2, surging human prosperity at the risk of destroying the ecosystems we live in



The sun supplies almost all energy to life on Earth

Surface Ecosystems

Buried organic matter is turned to fossil fuels over millions of years

Fossil Fuels

Humanity's Energy Sources

① Pre-Industrial

Living plants and animals

② Fossil Fuel Age

Living plants and animals

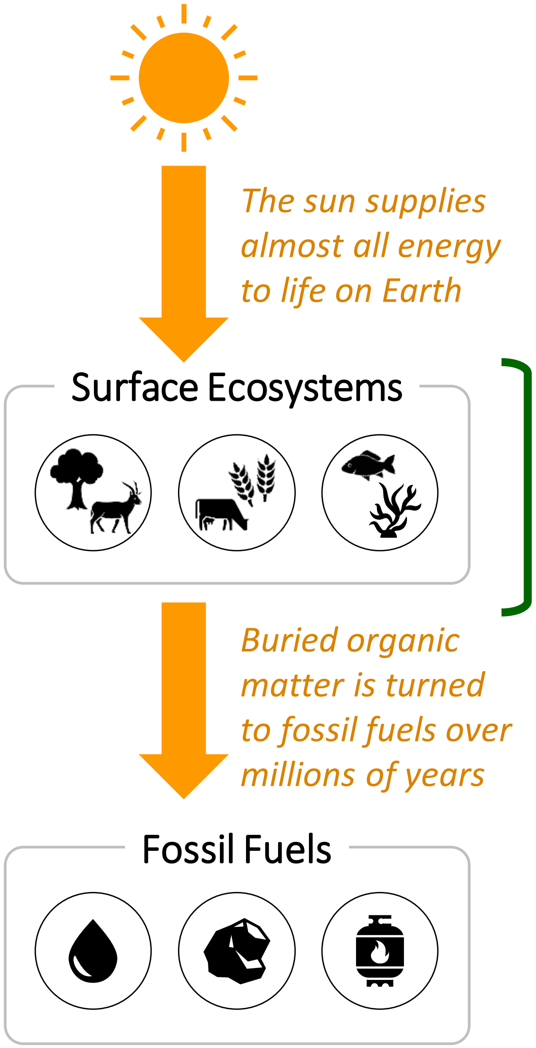
+ Fossil fuels

This energy access enabled 1700 to 2015 growth of:

- 12x *Global human population*[1]
- 170x *Annual global economic output*[2]
- 100x *CO_2 released annually from Earth's interior*[3]

[Link](#) for citations and additional notes

Human civilization is now capable of drawing energy directly from the sun instead of relying on other life to package it for us as fossil fuels



Energy Sources of Human Civilization

1 *Pre-Industrial*

Living plants and animals

2 *Fossil Fuel Age*

Living plants and animals
+ Fossil fuels

We can use this power to jump to our next phase – which wouldn't have been possible without fossil fuels as a stepping stone

3 *Freedom*

Living plants and animals
+ Renewable energy

Humans have always lived on the sun's energy**, but we now **have the technology to harness it directly*

Solar | Wind | Hydro | Biomass

**Even though we think of the sun as only directly harnessed through solar power, all pictured forms of renewable energy are fueled by the sun, whose energy drives wind, evaporation, etc.*

Slides 4, 5, 6

Slide 4

1: This source and this source provide good summaries. There's a lot more interesting detail in sunlight's interaction with Earth's atmosphere that isn't covered here. In addition to visible light, the sun emits UV light (which can be harmful to life) and its own IR light. These have complex interactions with many atmospheric gases, including ozone. Ozone protects life on Earth from most UV light, and is also significantly affected by human activity. However, the greenhouse effect is driven specifically by the visible light which is converted to IR at Earth's surface, so this slide focuses specifically on that part of the process.

Slide 5

1: Source and source, and also source

2: Multiple factors helped end the last Ice Age – warming likely began before the initial rise in CO_2, which then helped lock in further warming and rose rapidly until the modern age. More details at source, source, and source. Picture is from here.

3: Humanity's industrial fossil fuel use began in the 1700s, but the 1850-1900 average temperature was chosen as the standard "pre-industrial" baseline (source) since it's modern enough to have pretty reliable temperature data, but early enough that human-driven warming was still in the very beginning stages.

4: Source for +1°C warming, and source for the rise in CO_2 so far

5: Repeat of an earlier source for the data. Temperature and seas were higher here, at the same CO_2 level as today, since it takes a long time for climate to react to heat changes – for instance, major glaciers are now in decline, but will take centuries or millennia to melt at this rate. As a result, the damage we're experiencing so far is only a portion of what will eventually play out, if we stay at an elevated CO_2 level.

6: Information here, as well as this excellent image of a simulated Earth at this time (100% worth viewing in high definition), all from Alan Kennedy of the University of Bristol

7: This calculation is hypothetical. It would be impractically evil to extract anywhere close to all known fossil fuels, for cost and logistical reasons. Also, with a fraction of this heating, it would be tough for us to keep civilization running and extracting more.

Slide 6

1: Source for pre-industrial. The current total is growing so fast that it rapidly gets outdated. The prior source was from 2014 and showed 830 Gt in the atmosphere, while the value was 870 Gt by the time of National Geographic's September 2019 issue (page 86) – here's a link to the relevant graphic

2: 2019 analysis by the Deep Carbon Observatory, as cited here, here, and here

3: Source for historical emissions through 2018

4: Same source as citation 1

SOURCES

Slides 7, 8

Slide 7

1: Source. Ppm = parts per million, or the number of CO_2 molecules per million molecules in the atmosphere. Note that when Earth's climate shifts, the poles' temperature changes tend to be more extreme than the rest of the planet's.

2: Source, and here's a source for day-by-day data

3: Source. I promise this is my only citation of Wikipedia.

4: The exact mechanics of the PETM are still debated. Here's my source for these numbers, which seem to be the mainstream interpretation, but there are other sources like this that claim a huge release of seabed methane also played a major role. Either way, the PETM is a good upper limit for how fast natural climate change can warm Earth – it's the fastest warming incident we can find evidence for, at least up until 700M years ago, beyond which things get fuzzy. Since these are the numbers required for that change to be driven by CO_2, it's a solid benchmark for how rapid a natural CO_2 release *could* be. Since even a fully-CO_2 explanation would imply a CO_2 release rate that's tiny compared to our emissions today, it's fair to say that based on our current understanding, our emissions today are unprecedented in the period of Earth's history that we can assess.

5: 2019 rate, source (annual mean growth rates). Note this is *net* addition to atmosphere – we emit roughly twice this, but as covered on slide 5, land and oceans absorb half our emissions

6: Source

7: See citation 4 for the logic here!

Slide 8

1: Source, source, and source (annual mean growth rates); values rounded to closest 5 ppm. "Net Emissions" is total added to the atmosphere: human emissions minus extra absorbed by land and oceans. I use 2019's rate since 2020's was so impacted by COVID-19.

2: Source (NASA Global-mean monthly, seasonal, annual means, 1880-present)

SOURCES

Slides 9, 11, 12

Slide 9

1: Pathways source is the fantastic Our World In Data, which in turn got it from another amazing source, the Climate Action Tracker. I made slight tweaks to the data between 2010 and 2014 to reflect what actually happened during that time period. The historical CO_2e numbers end in 2014 because that was the base year for all the calculations, but emissions growth continued along the orange and red paths until the global economic impact of the COVID-19 pandemic led to a sharp drop in emissions. At the time I'm writing (November 2020), whether that will prove just a temporary fall, or is the beginning of a future down-slope in emissions, remains to be seen.

2: CO_2e means CO_2-equivalent. This metric gives us an objective standard that can show the effects of emissions not just of CO_2, but also of other greenhouse gases like methane. As a result, this number is higher than for CO_2 alone, but a more realistic metric of human civilization's full greenhouse gas emissions. For most of this article, I've focused on CO_2 alone to keep things simple, and because it's much easier to get datasets of CO_2 than CO_2e. Since CO_2e involves lots of different gases and calculations of their relative warming impact, it's more complicated to measure. That said, when it's available and reliable – like now – it's the best metric to use.

Slide 11

Due to overlap, here are a couple of sources that cover all of these. 2019 U.S. Army report covering impacts like sea level rise, severe weather driving higher food stress and humanitarian crises, loss of freshwater supplies, wider range of disease-bearing insects, and more intense, longer droughts. 2016 U.S. Intelligence Community report covering more severe heavy rainfall, floods, droughts, cyclones, heatwaves, crop failures, mass deaths in marine ecosystems, wildfires, blackouts, infrastructure collapse, disease outbreaks, sea level rise, ocean acidification, air quality degradation, and other threats. Also, source from NASA on the science behind warmer air holding more moisture. Climate change: Don't try it at home.

Slide 12

Evidence that CA's fire seasons are rapidly becoming worse is extensive (here's one source), and evidence that "water" risks are also increasing includes the 2017 Oroville Dam spillway crisis (source), mentioned in more detail in the following slide. That said, there is currently no set standard aside from the costs of damages, which is determined by a lot of factors aside from weather severity, to compare the intensity of different types of severe weather events. This is one of the major factors that makes concerted climate action difficult – without being able to prove exactly how much money it costs, it's harder to exactly calculate the cost savings we'll get for investments in preventing it. There's a bit more on this on the following slide

SOURCES

Slides 13, 14

Slide 13

1: Source – as of November 3rd, 2020

2: Source

3: Source

4: The costs vary widely depending on what you count. $24B is from this climate.gov analysis, but my guess is that it focuses on a narrow range of direct costs. Here is a middle-ground academic study alleging that the cost was $148.5B, including $27.7B in capital losses – close to that $24B estimate – along with $32.2B in health costs and $88.6B in indirect losses, like lost economic activity due to the fires. The $350B estimate is here, from AccuWeather, with even higher estimates of indirect losses – it estimates that CA itself lost $400B, but that other states would gain slightly from economic activity that shifted out of CA to them, resulting in a $350B net loss for the U.S. overall.

5: Source

6: Source

Important note: though climate change is a huge driver for CA's increasingly terrifying fire seasons, there are other human-caused issues as well. Over the last century, U.S. authorities have heavily suppressed fires (source and source), which are a natural feature of the Western U.S. ecosystem. This allows unnatural levels of fuel to build up, so when fires break out of control, there's more for them to burn. Housing has also pushed further into wilderness areas, supported by laws forcing insurance providers to keep offering fire insurance for homes in high-risk areas. The more areas have to be protected, the more fires have to be suppressed, and the worse the problem gets. There are now major efforts to rethink U.S. fire mitigation policy, including use of more controlled, preventative burns. Some efforts (source) coordinate with local indigenous communities, whose traditional fire management techniques were honed before industrial firefighting capabilities arrived. (For my actual job, I've analyzed the U.S. market for firefighting aircraft, so have a ton of research on this if anyone's interested in a mini deep-dive). That said, it's still unclear how much better policy can fix, when climate change is having such a devastating impact on the natural conditions that drive fires.

Slide 14

1: It will improve further as computer modeling of climate and weather, which are very hard to simulate, continues to get better (source and source)

2: Source

3: Source

4: Source – it was likely to happen less than once every 80,000 years without human-caused climate change, and 600x more likely (less than once every 130 years) with human-caused climate change. The wildfires released more CO_2 than Switzerland or Norway do annually, and sped up permafrost melt, which will be covered soon.

5: Almost all sources in this section are relevant for this, but I think the best summaries come in the U.S. Army and Intelligence Community assessments cited on slide 10

Slides 15, 16, 17, 18, 19

Slide 15

1: Source

2: Source

3: Source

4: Source

5: Source

6: Source is the 2016 U.S. Intelligence Community report from earlier

7: Source

8: Source

9: Source

10: Source for land burned. Source for death toll, with 30 people killed directly by the fires and smoke accounting for hundreds more deaths and thousands of hospitalizations. Source for the animal death toll, which is especially critical for some of Australia's unique large mammals already facing habitat challenges. Source for smoke making a full circuit of the globe

Slide 16

1: Source

2: I usually focus on CO_2 to be concise, but methane and other greenhouse gases also have a major impact on climate change – see footnote 2 on slide 9 for more detail.

3: Source

4: Source

5: Source

Slide 17

1: Picture – with hilarious context – at source

2: Source, and here's a source that looks at the even more extreme change in volume

3: Source

4: Source

5: Source

Slide 18

1: All data in this column is from source and source

2: All data in this column is from source and source

3: Source – the two cases are a) The current fossil fuel share of energy continues; and b) Enough clean energy is adopted to reach the 2°C pathway. The savings are largely from avoided air pollution costs, but also take into account climate change damage costs (e.g., increased disaster recovery costs)

Slide 19

1: International Renewable Energy Agency 2019 report, here. The 2°C plan requires that $95T in already-expected energy investments by 2050 are partially realigned to clean tech, and another $15T ($500B per year) is also invested, for $110T total by 2050. For reference, the International Energy Agency's 2020 report shows 2018-20 avg. annual investments in fossil fuels at $880B, and in renewables at $330B.

2: Source from Statista, with research originally from a major Greenpeace report

3: From a 2019 report by Moody's, here

Slides 21, 22

Slide 21

1: Ppm = parts per million. Values from here and here, rounded to nearest 5 ppm.

2: 2019 rate, source (annual mean growth rates). As noted before, I used 2019's rate because 2020 was so affected by COVID-19. Note this is *net* addition to atmosphere – we emit roughly twice this, but as covered on slide 5, land and oceans absorb half our emissions

Slide 22

1: Efficiency investments include things like more efficient lightbulbs and engines, better insulation, and use of "waste" heat. Since they're less complex and controversial than other parts of this case – even fans of fossil fuels usually agree that efficiency is good and waste it is bad – I decided not to cover it in detail. More information at sources like here.

2: Energy that's "Used Directly" doesn't go through the electricity grid. Right now, this is normally fossil fuel delivered to a user and burned there – say gasoline for non-electric cars, natural gas for heating homes, and coal for steelmaking. That said, it can also include renewable, or renewably sourced (more later), energy used on-site. For a further breakdown of what this looks like on a source-by-source basis, see here for a more detailed version of the chart for the U.S. in 2019, or the original report here.

3: Nuclear is "clean" in terms of carbon – it emits none – but it's not renewable, since it uses radioactive fuel. It's controversial due to concerns about safety and hazardous waste. Environmentalists are split on nuclear: some argue that modern reactors, practices, and waste disposal are very safe, so nuclear should be expanded to help replace fossil fuels faster. Others are opposed, seeing nuclear as fundamentally unclean. Since nuclear is a great partner to renewables – it offers predictable baseload power, to balance out intermittent solar and wind generation – whether it's "clean" is a hugely important debate. There's far more complexity, and excellent points on each side, than I can cover here, so I'm giving nuclear a "Clean-ish" label and avoiding further debate for now.

SOURCES

Slides 23, 24, 25

Slide 23

1: Source, costs are "levelized" over the expected lifetime of a given electricity generation facility. These are top-level values that summarize global standard costs, but the cost of any given electricity source varies across regions and times. Different parts of the globe have different levels of sun and wind, and different access to fossil fuels, resulting in significant price differences.

2: Clean electricity could include nuclear, depending on who you ask, but I'm focusing purely on renewables here for simplicity – please see slide 23 footnote 3 for why I'm not diving fully into nuclear in this piece. I'd like to write more about whether it has a place in our evolution beyond fossil fuels, but given the debate's complexity, I'm avoiding further detail for now to keep things concise. If anyone aside from my family and friends (thanks guys!) reads this piece and I get to do more of this, it's my first candidate for a follow-up deep dive.

3: Source, U.S. Energy Information Administration, 2019 report. In terms of renewables adoption by 2050, this is one of the more pessimistic mainstream sources.

4: Source, Bloomberg New Energy Outlook. In terms of renewables adoption by 2050, this is a middle-of-the-road estimate.

5: Source. From IRENA, the International Renewable Energy Agency, using its 2°C path ("ReMAP Case"). This case assumes additional investment in adoption of clean energy – see slide 18 footnote 1 for additional details on exact numbers.

Slide 24

1: Source for detail on this tech in California, a leading U.S. renewables market

2: Solutions include new types of batteries (source) or other approaches like storing heat by pumping it into salt (source) or building gigantic cranes that lift and lower huge blocks to store and release energy (source).

3: Northern Germany is a key example (source), and the U.S. has multiple separate efforts ongoing (examples here, here, and here)

4: A recent report on U.S. grid decarbonization highlights transmission investments as a critical component

5: Right now, these plans focus on hydrogen (more detail on next slide). Example proposals here, here, and here

Slide 25

1: Electric vehicles are a 1%, but fast-rising, share of global cars (source). Electric heat pumps are a high-efficiency replacement for traditional gas heating and A/C (source). They're market-ready, but in the U.S., aren't yet common to install. CA, as normal, is leading the way here (source).

2: Steelmaking needs over 1,000°C and renewables today only reach ~500°C (source), but a startup claims it can hit 1,000°C with solar (source). For aviation, current batteries only have enough power-to-weight for small planes on short flights (source), but future tech could change that.

3: This makes "green" hydrogen. Most hydrogen is currently made non-cleanly, using fossil fuels ("blue" or "grey"). More detail here and on slide 25 footnote 5.

SOURCES

Slides 26, 27

Slide 26

1: There are more potential methods, but I felt that these three were the best representative examples at the time of writing (late 2020). All data on the technologies, including their withdrawal rates and cost estimates, is from source. For BECCS and Global Forestation, "Potential Rate" is by 2050. Their upper limits are set by land area requirements, accounting for the land needed for agriculture to sustain the world's current food supply. All numbers for DAC are still tentative, since there's still a lot more research and development to do before these plants are deployed at scale. For DAC, the report gave a more cautious 2050 estimate and a higher 2100 one. I used the 2100 one to give full context. It's not clear what the upper limit for DAC would be– in theory, we can build as much of it as we need. However, current methods are electricity-intensive, so cleanly powering a lot of DAC plants will require building a lot of renewable electricity capacity.

2: Source, source, source; chart rounded to nearest 5 ppm.

3: 2019 rate, source (annual mean growth rates). As noted before, I used 2019's rate because 2020 was so affected by COVID-19. Note this is *net* addition to atmosphere – we emit roughly twice this, but as covered on slide 5, land and oceans absorb half our emissions. I originally used total emissions (twice this total) in this chart, because if we only balance out 2.5 ppm, we'll still be releasing additional emissions that continue to impact the ocean especially and damage marine life. I finally decided to switch back to 2.5 ppm to match the rest of the slides and not confuse readers. But to get to real net zero, we need to balance out more like 5 ppm.

Slide 27

1: Source, source, and source. The most common example of this is the 1991 eruption of Mt. Pinatubo in the Philippines, which released 15M tons of sulfur dioxide, reflecting ~1% of sunlight and dropping global temperature by 0.6°C for over a year. (Exact numbers vary by source, and by the time of the measurement after the eruption. I used the sources here and here).

Slide 28 (part 1 of 2)

Slide 28 (part 1)

1: IRENA 2019 report. See slide 17 footnote 1 for detail – this additional investment does not include current energy investment plans.

2: Source

3: Smith and Wagner, 2018 (here); they selected 2033 assuming it would take a while to get this started, and numbers assume that future emissions track the IPCC's pessimistic RCP 6.0 scenario. The 95 aircraft only cover the following 15 years (i.e., through 2047), continuing to assume the RCP 6.0 path – so if actual emissions by then are lower than RCP 6.0, we'd need fewer aircraft

4: Source

5: A lot to talk about here. Below are three points, and there's a fourth on the next slide.

a) Solar geoengineering could destabilize global rainfall. Reducing incoming sunlight can reduce evaporation, which reduces rain and snow (source). However, a study (here) used a high-definition climate simulation to project that slower geoengineering – just cutting the pace of warming by half, not stopping it completely – wouldn't have this side effect. I used this ½ pace of SRM as the standard in the profile. This is one area where only real-life experiments, not simulations, will give us a conclusive answer.

b) Sulfur aerosols in the upper atmosphere can reduce the thickness of the ozone layer (here), which protects Earth's surface from much of the sun's dangerous UV light. Researchers have proposed calcium carbonate – $CaCO_3$, a safe compound used as an additive in toothpaste and food – as an alternative with the same reflective effect as sulfur aerosols, but that doesn't damage the ozone layer (here). We need more experiments to test it though. Since sulfur dioxide is already naturally released by volcanoes, we know that it'll do the job, while there's no natural experiments that put $CaCO_3$ in the stratosphere.

c) There's active debate over potential side effects of SRM. One prior suggestion was that it could reduce plant growth, but studies have shown it actually increase growth – slightly less sunlight would reach Earth's surface, but the light that gets through would be slightly more diffuse, which benefits plants (here), resulting in a net positive effect. That said, scientists have raised other potential effects, and there are probably plenty that no one's thought of yet. To know more, we need experiments. Some argue that since there might be side effects, we shouldn't do any testing. Personally, I can't reconcile that stance with the danger that we face from climate change. Ideally, global decarbonization moves fast enough that we never need geoengineering, but the threat is so big that I think it would be criminally negligent not to look into backup options.

Slide 28 (part 2 of 2)

Slide 28 (part 2)

d) There are geoengineering proposals aside from high-altitude release of reflective particles. One of the most prominent is marine cloud brightening, in which seawater or salt is drawn from the ocean and sprayed into the air, where it helps form or expand clouds (source). More clouds means more sunlight is reflected back to space, and less is absorbed by the ocean as heat. Even though these proposals use purely natural components and objectives and would operate on the ocean, far from inhabited areas, they've had a tough time getting funding given the strong negative reactions against geoengineering in general. Here's a source on a recent test in Australia trying to help protect the rapidly-dying Great Barrier Reef, and here's a source writing about it that's fiercely opposed to any geoengineering. (In case it isn't clear, I strongly disagree with the opposition source). In this piece, I focused on SRM because a lot more studies have been done on its costs, variants, side effects, etc. than on marine cloud brightening.

6: This "moral hazard" is an argument that many anti-geoengineering advocates use to make the case that not only should we commit to not using geoengineering, we should refuse to allow any research on geoengineering, because just looking into it could result in complacency and inaction on climate change. I see their point, even though this argument is kind of like saying that you should take parachutes out of planes, because if the pilots think they might survive a crash, they won't be as focused on flying well. Optimistically, I'd hope that we can motivate people to decarbonization out of hope, not fear, and be rational about which options are availableand which make the most sense to get us where we need to go. The leading scientists researching this form of geoengineering are also extremely clear that if this is ever used, it must be used only as a temporary mitigation measure to buy time for real decarbonization– it's not a long-term solution. However, there's still widespread resistance to exploring the idea at all, and the political controversy around geoengineering has made it hard for researchers to get support for experiments (here). Though the idea has been around for decades, research has been largely limited to digital climate modeling and lab testing. At the UN in 2019, countries including Switzerland and New Zealand tried to pass an effort to begin an initial report on potential geoengineering governance options, but it was shut down for unknown reasons by the U.S., Saudi Arabia, and Brazil (source) for unclear reasons.

SOURCES

Slides 29, 31

Slide 29

Many of these were previously cited on other slides, but I'm re-citing them here.

1: Emissions are in CO_2e, or "CO_2-equivalent," a metric of warming that compares all greenhouse gases' heating impact to the impact of CO_2 to allow standard comparisons across different gases. See slide 8 footnote 2 for a deeper dive on CO_2e, and why I don't use it in other slides. The pathways source is the fantastic Our World In Data, which in turn got it from another amazing source, the Climate Action Tracker. See slide 8 footnote 1 for some additional detail on minor tweaks I made to the data to reflect what's happened since it was compiled, and why historical CO_2e numbers end in 2014 (emissions growth has continued along the orange and red paths until the global economic impact of the COVID-19 pandemic).

2: To be specific on costs, a 2019 report by Moody's here projects climate change costs by 2100 of $54T for 1.5°C warming and $69T for 2°C. It doesn't give exact estimates for higher warming, but they'd likely accelerate at a higher proportion than each increase in warming, since warming damage compounds (see chart on page 4 of the report as an example). Current global fossil fuel air pollution costs are $2.9T/year (source), and these should correlate closely with the amount of fossil fuels we burn. The IRENA 2019 report estimates that every $1 invested in its by-2050 investment plan, to hit a 2°C path, to bring $3 to $7 payoff.

Slide 31

1: This is a simplified display of the full chart, available here

2: Total energy in "Energy Use" (100) doesn't add up to total in "Energy Destination" (76) because of energy loss during transmission and conversion. Further loss happens at each destination. The worst offender is transportation, where over ¾ of input energy is lost – it's just not as efficient to burn fossil fuels in millions of small car engines as it is in big, central facilities.

3: See slide 20 footnote 3 for detail on why I treat nuclear separately.

4: Efficiency investments include things like more efficient lightbulbs and engines, better insulation, and recovery of "waste" heat. Since they're less complex and controversial than other parts of this case, I decided not to cover in detail. More information at sources like here.

Slides 32, 33, 34

Slide 32

1: Our World in Data pages here and here. TWh numbers are rounded to closest 100, and renewable shares are rounded to nearest 1%

2: See slide 20 footnote 3 for detail on why I treat nuclear separately.

Slide 33

1: Data from Our World In Data's fantastically detailed greenhouse gas emissions data page, here

Slide 34

1: Source for historical human GDP. GDP is Gross Domestic Product, an imperfect but generally accepted metric of goods and services production. 170 is rounded up, the exact multiple is 168

2: Source for historical human population. 12 is rounded down, exact is 12.2

3: Compares the roughly 300M-400M metric tons per year in natural geological emissions (through volcanoes and other routes for carbon to leak from the interior), as assessed by the Deep Carbon Observatory's 2019 report (cited here, here, and here) to the 35B metric tons released by humans in 2015 (source is Our World in Data). The middle of that natural range, 350M, is 1/100th of 35B