The Global Energy Transition

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How to Read This Presentation

- This is the first of two presentations covering the global energy transition.
- This presentation provides an overview of the global climate challenge and potential solutions to reach net-zero emissions.
- The second presentation provides an overview of global climate legislation, with a focus on the U.S. Inflation Reduction Act (IRA) and its implications.
- Each section of this presentation builds on the prior and assumes no prior knowledge about the discussed topic. At the end of each section, there will be a slide with links to further short readings and YouTube videos to reinforce your learning.
- By the end of this presentation, you should have a good understanding of the global climate challenge, potential solutions, and some of the tradeoffs associated with each.

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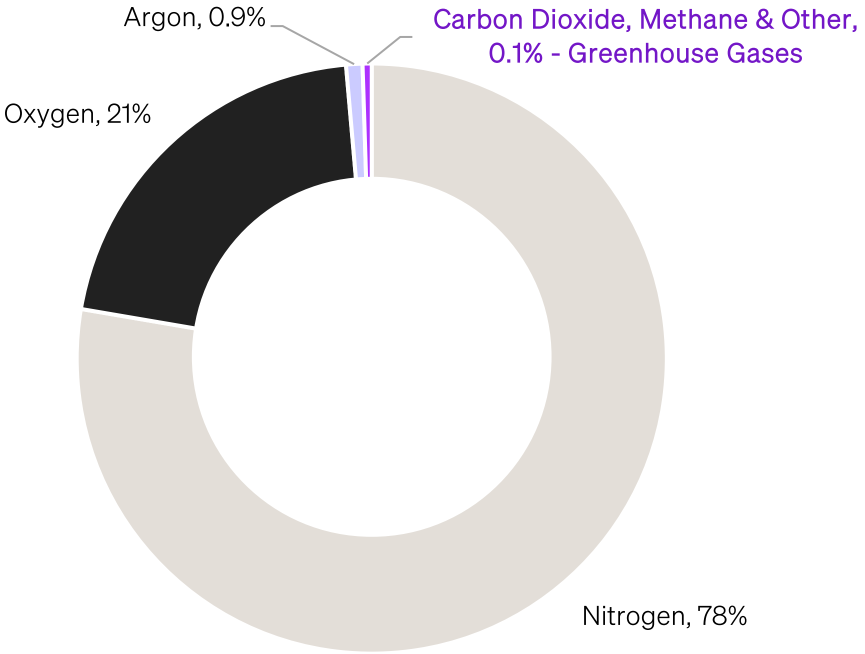
CHAPTER 01

An overview of climate change

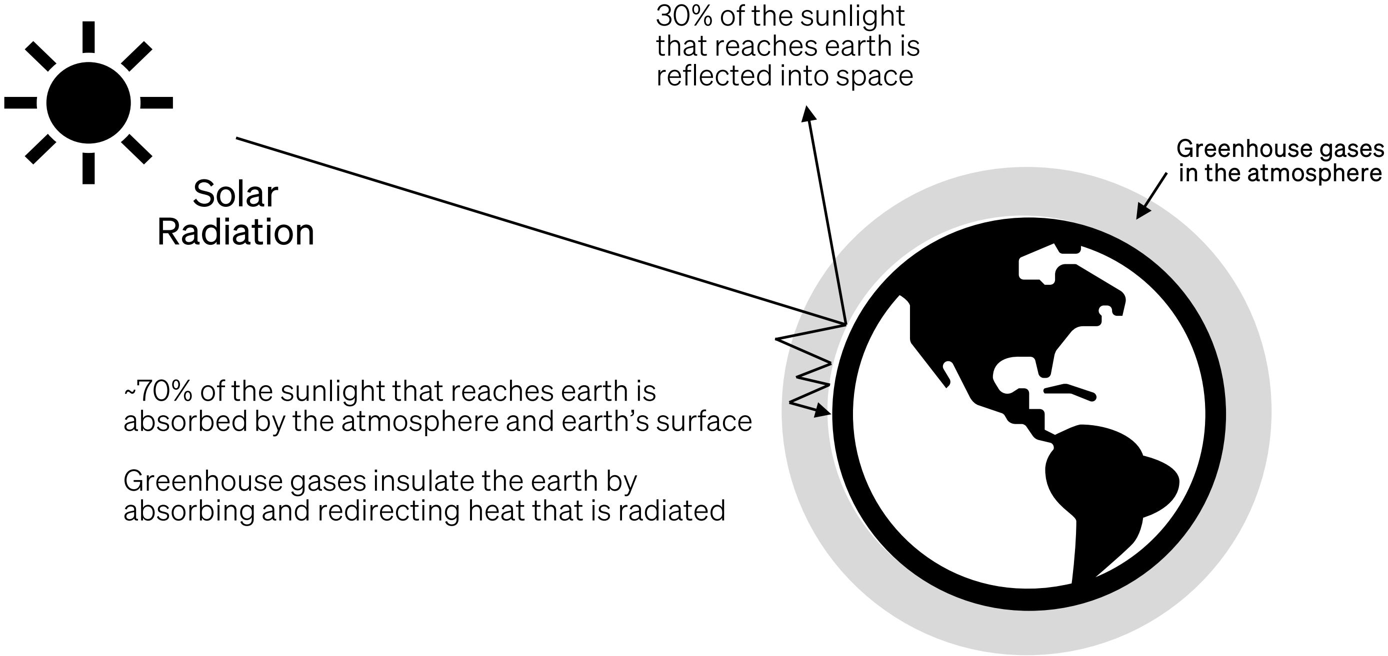
The environment 101

The Earth's Atmosphere Is Composed of Various Gases Including 'Greenhouse Gases'



Source: NOAA

Greenhouse Gases in the Atmosphere Are Necessary to Keep the Earth Warm

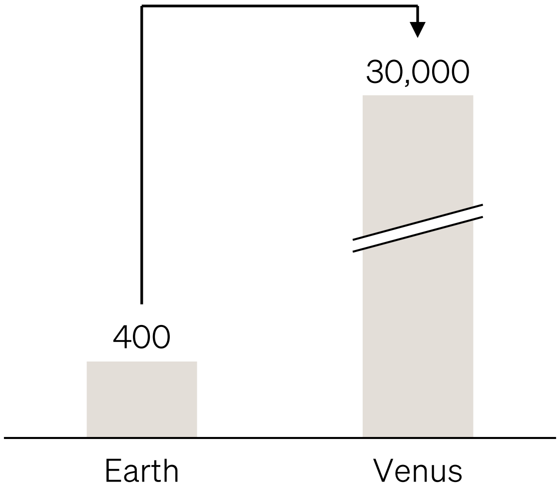


Source: EPA, World Meteorological Organization

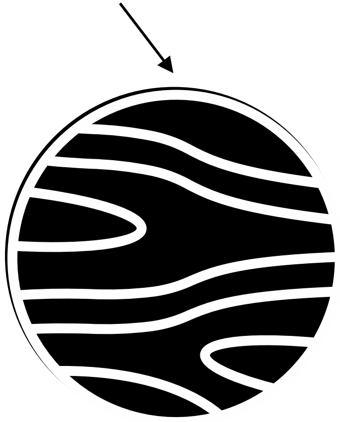
But Excessive Concentration of Greenhouse Gases Can Lead to Dangerous Warming

Venus is an extreme example of what happens when the concentration of greenhouses gases is too high

CO2 Concentration in Atmosphere (parts per million)



Venus has a surface temperature of 464°C, which is hot enough to melt lead



There Are Four Main Types of Greenhouse Gases

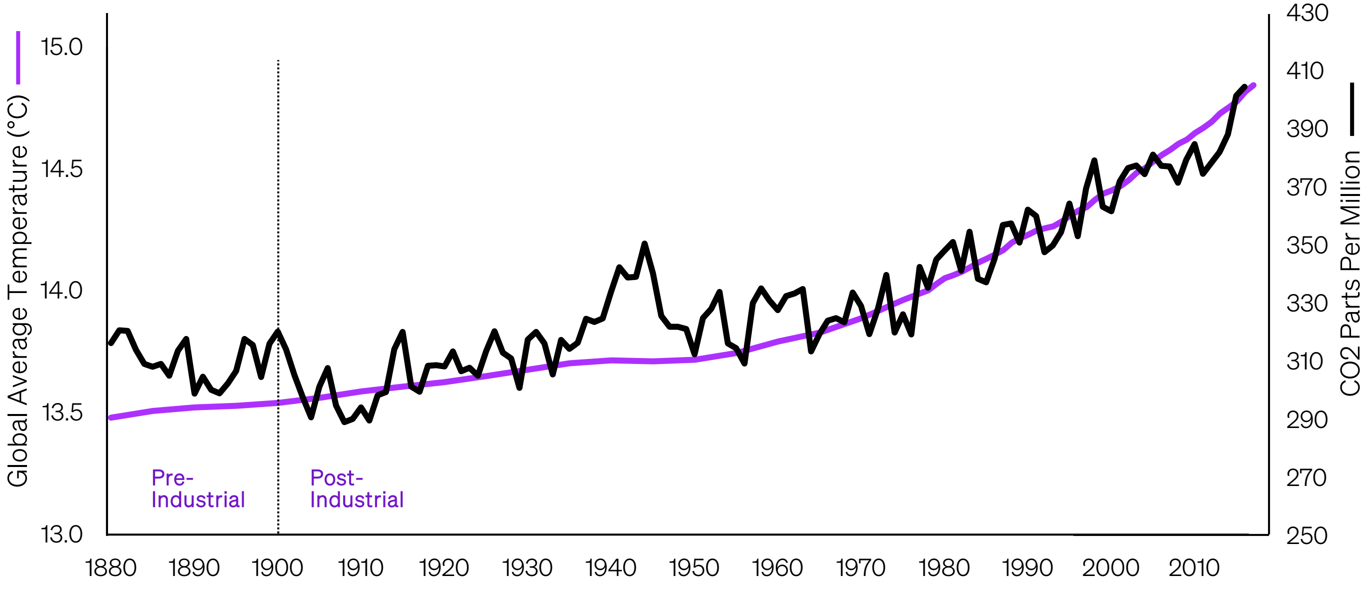
‘Parts per million’ refer to the number of greenhouse gas molecules per million molecules of dry air

Lowest warming potential, highest concentration → Highest warming potential, lowest concentration

	Carbon Dioxide (CO_2)	Methane (CH_4)	Nitrous Oxide (N_2O)	Fluorinated Gases
Concentration in atmosphere	~420 parts per million	~1,900 parts per billion	~330 parts per billion	~100 parts per trillion
Lifetime in atmosphere	~300-1,000 years	~12 years	~110 years	A few weeks to thousands of years
Removal from atmosphere	Removed by ocean, forest and other carbon sinks	Removed by oxidation into carbon dioxide and water	Removed by sink or destroyed through chemical reactions	Gradually broken down by UV in upper atmosphere

Source: NOAA, IEA, NASA

Global Temperatures Have Increased as the Concentration of Greenhouse Gases in the Atmosphere Has Risen



Dive Deeper…

Further Reading & Watching

Reading:

- The Atmosphere: Getting a Handle on Carbon Dioxide – NASA
- Greenhouse Effect 101 – National Resources Defense Council
- Climate Change: Global Temperature – Climate.gov
- Scientists Assess Potential For Super Greenhouse Effect in Earth's Tropics – NASA

Watching:

- The Carbon Cycle – Ted Ed
- "What is the Carbon Cycle" – NOAA
- Greenhouse Effect and Greenhouse Gases – Khan Academy
- Global Temperature Anomalies from 1880 to 2019 – NASA

Why do global temperatures matter?

A warmer climate changes weather patterns to make wet areas wetter, and dry areas drier. This could lead to extensive flooding in some regions, and water shortages in others

Leading economies have committed to reaching net-zero emissions by 2050 to keep warming to 1.5°C above pre-industrial temperatures

Source: NRDC

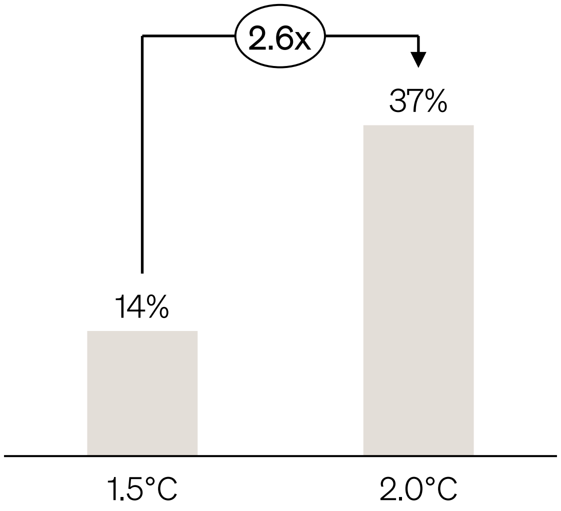
While even 1.5°C of warming could lead to harmful global consequences…

Source: United Nations

The implications of 2°C of warming are even worse

More Than a Third of the Global Population Could Experience Severe Heatwaves at Least Every 5 Years

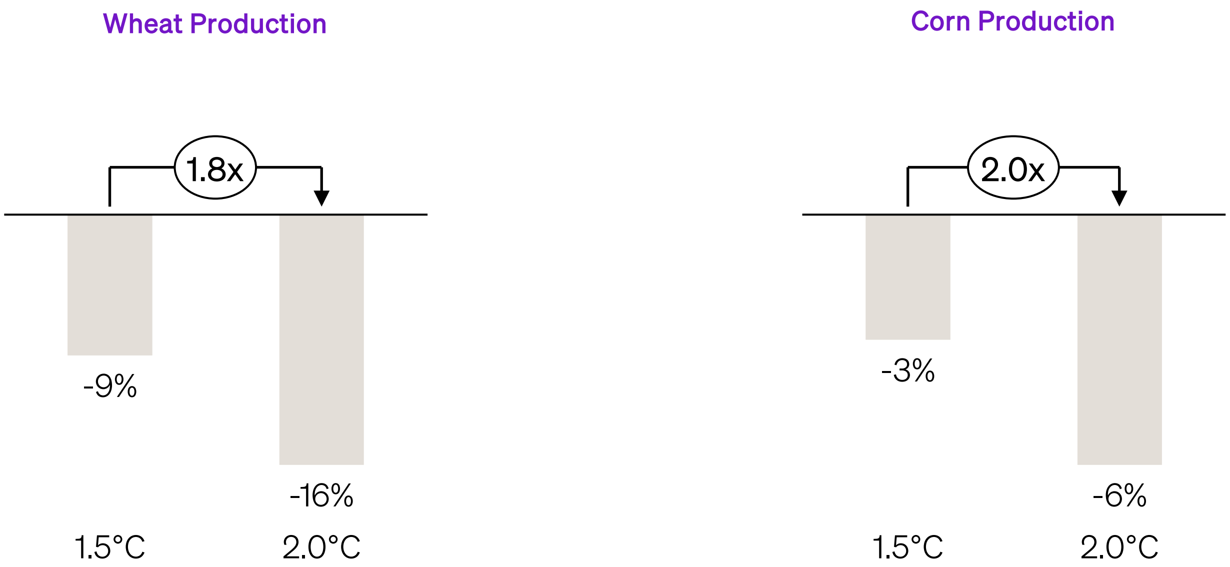
% of the global population experiencing severe heatwaves



Source: NASA

Widespread Food Shortages Could Arise in Southern Africa, The Mediterranean, Central Europe and The Amazon

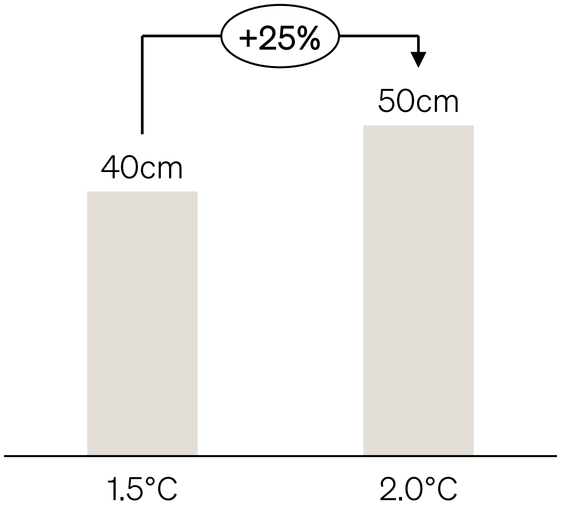
% decrease in crop yields in tropical regions



Source: NASA, CarbonBrief

Over 70% of Earth's Coastlines Could See Sea-Levels Rise By 50cm, Resulting in Extensive Coastal Flooding

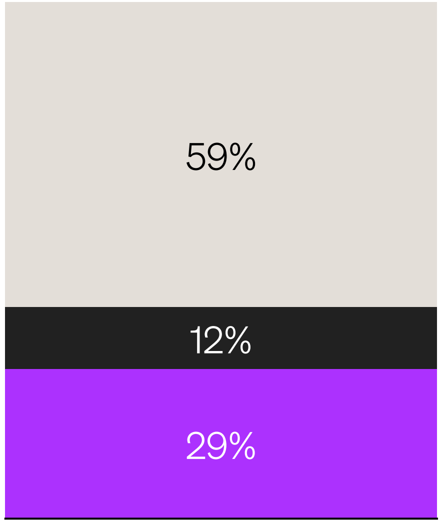
Rise in sea level by 2100 relative to 2000



Source: NASA, CarbonBrief

More Than 40% of the Permafrost in the Arctic Could Disappear

The Arctic Ocean would go from seeing ice-free conditions in the summer once every 100 years to once every 10 years

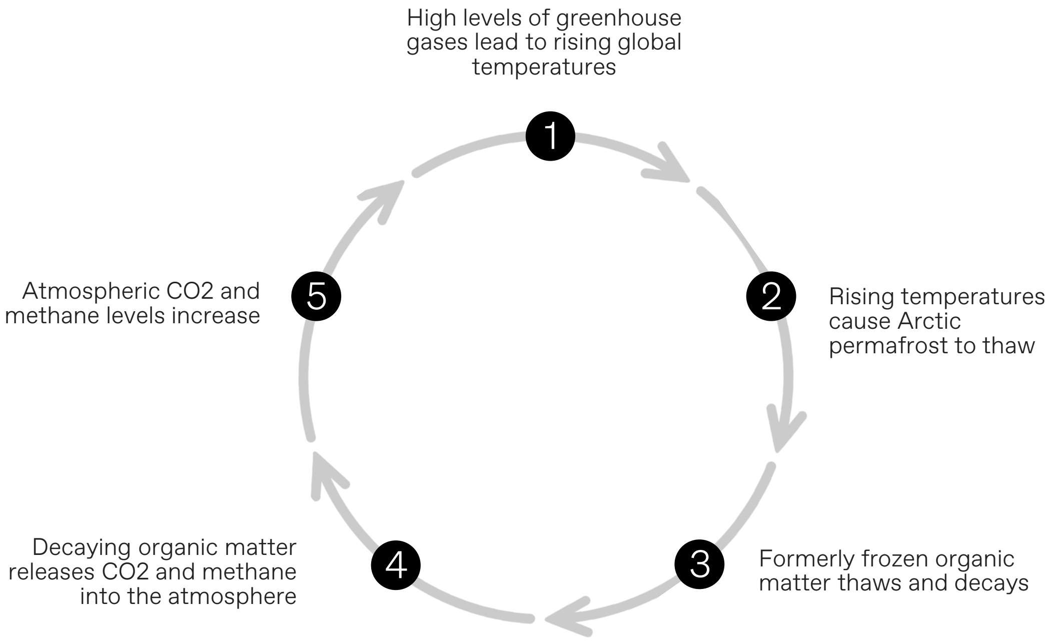


% of permafrost remaining at 2.0°C of warming

% of additional permafrost lost at 2.0°C of warming

% of permafrost lost at 1.5°C of warming

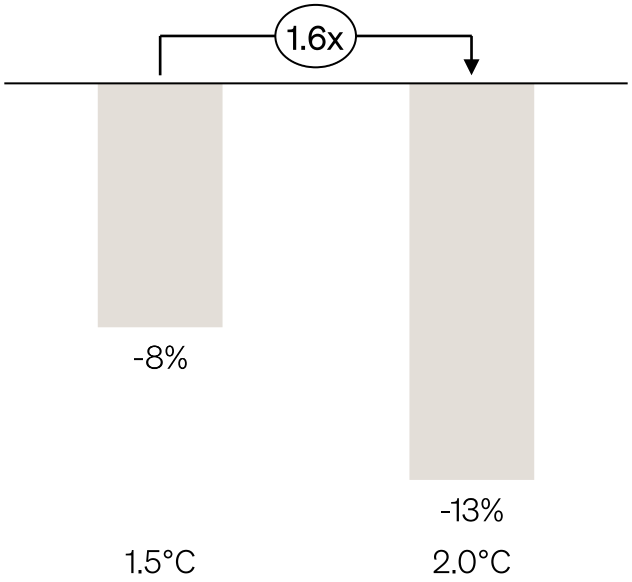
Thawing of the Arctic Permafrost Could Result in Feedback Loops That Accelerate Global Warming



Source: The Arctic Institute

All of This Could Lead to Harmful Economic Consequences

Global Per Capita GDP in 2100



Source: NASA, CarbonBrief

Dive Deeper…

Further Reading & Watching

Reading:

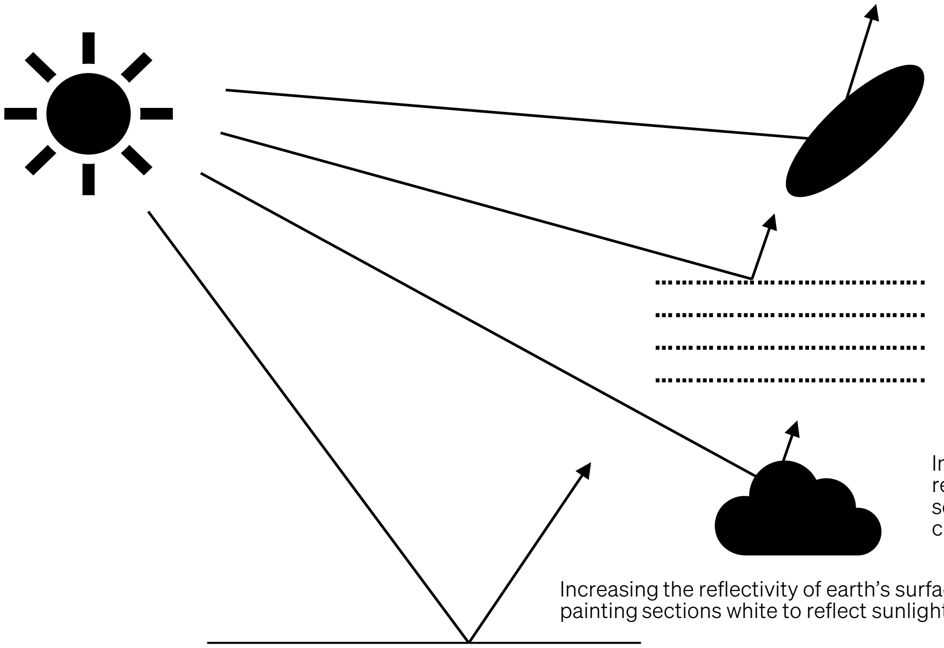
- The Effects of Climate Change – NASA
- The Impacts of Climate Change at 1.5C, 2C and Beyond – CarbonBrief
- How Thawing Permafrost Is Beginning to Transform the Arctic – Yale Environment 360

Watching:

- Why a Half Degree Rise in Global Temperature Would Be Catastrophic – Seeker
- Climate Change: How Half a Degree Could Change the World Forever – BBC Ideas

There are two methods to prevent further warming

Reflecting More Sunlight Back into Space



Space-based reflection methods including giant mirrors to reflect sunlight back into space

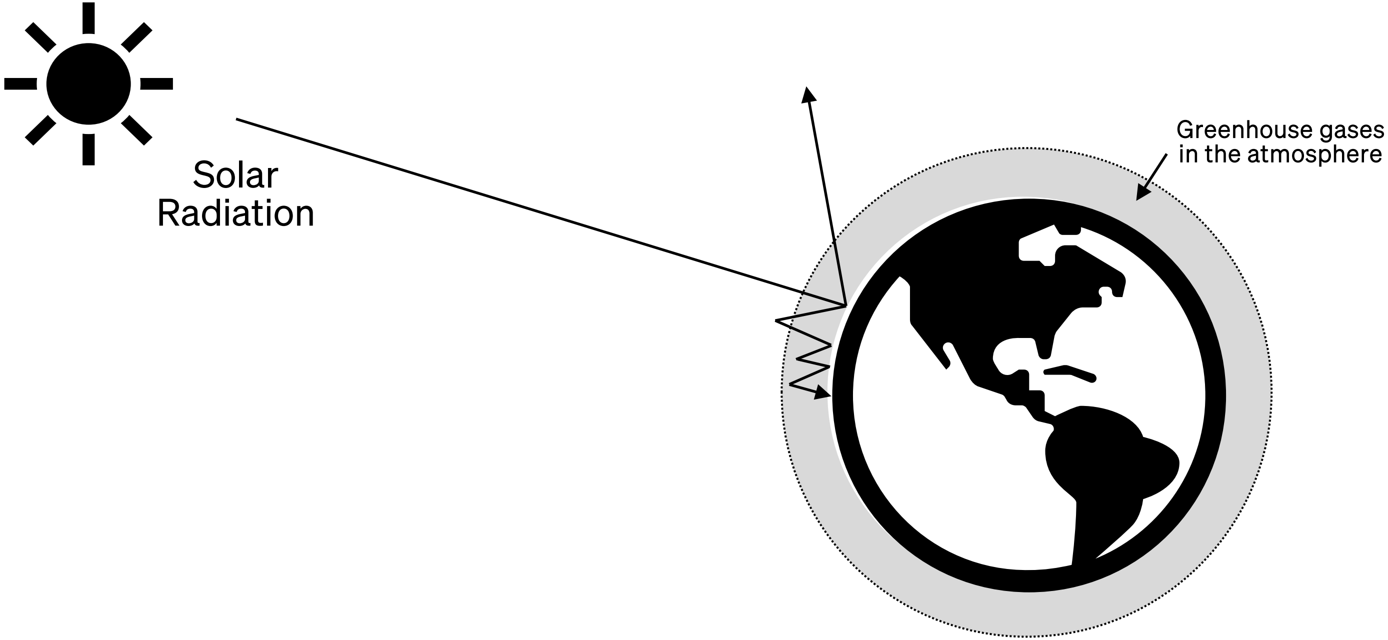
Increasing the amount of stratospheric aerosol (SAI) by spraying tiny particles into the atmosphere that can reflect sunlight

Increasing the reflectivity of marine clouds by spraying tiny seawater droplets into the air to make clouds whiter and more reflective

Increasing the reflectivity of earth's surface by painting sections white to reflect sunlight

Source: NOAA

Or Restricting the Concentration of Greenhouse Gases in the Atmosphere



Source: EEA

Reflecting sunlight back into space poses harmful potential implications for global weather, so the world is focused on reducing greenhouse gas emissions

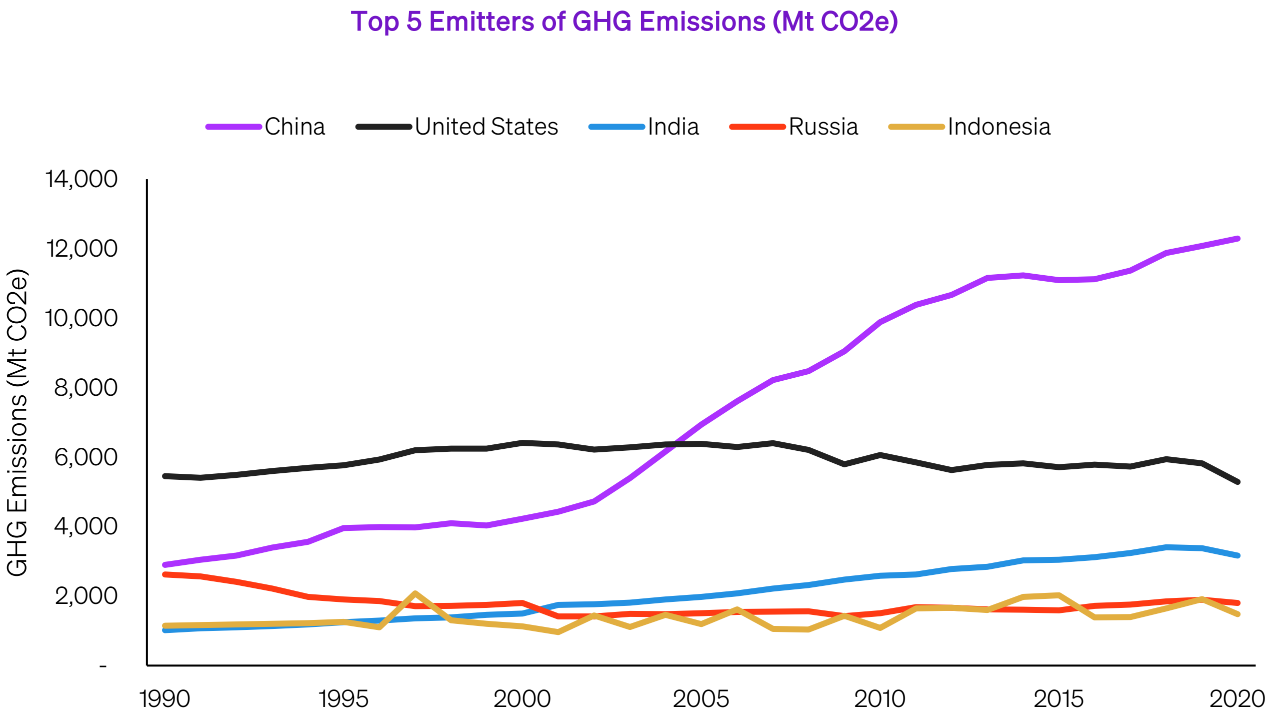
CHAPTER 02

Sources of U.S. emissions

The world emitted 55 billion tons of greenhouse gases in 2022

Source: Our World in Data

The United States is the Second Largest Global Emitter of Greenhouse Gases

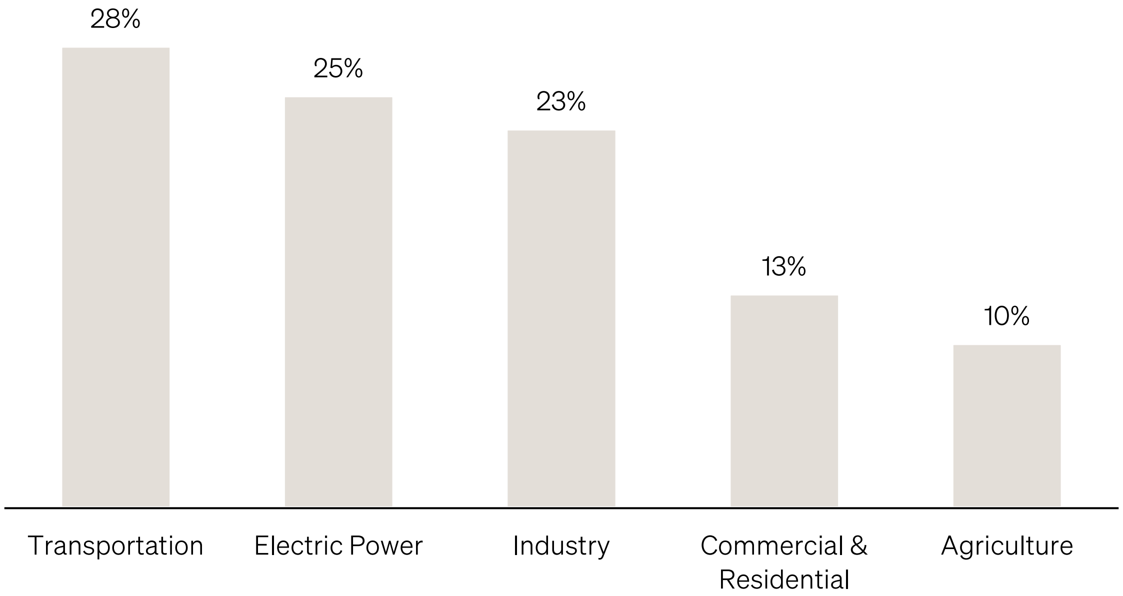


Source: ClimateWatch

Where do these emissions come from?

Greenhouse Gas Emissions Are Present Across Every Major U.S. Sector

Total U.S. Greenhouse Gas Emissions by Economic Sector, 2021



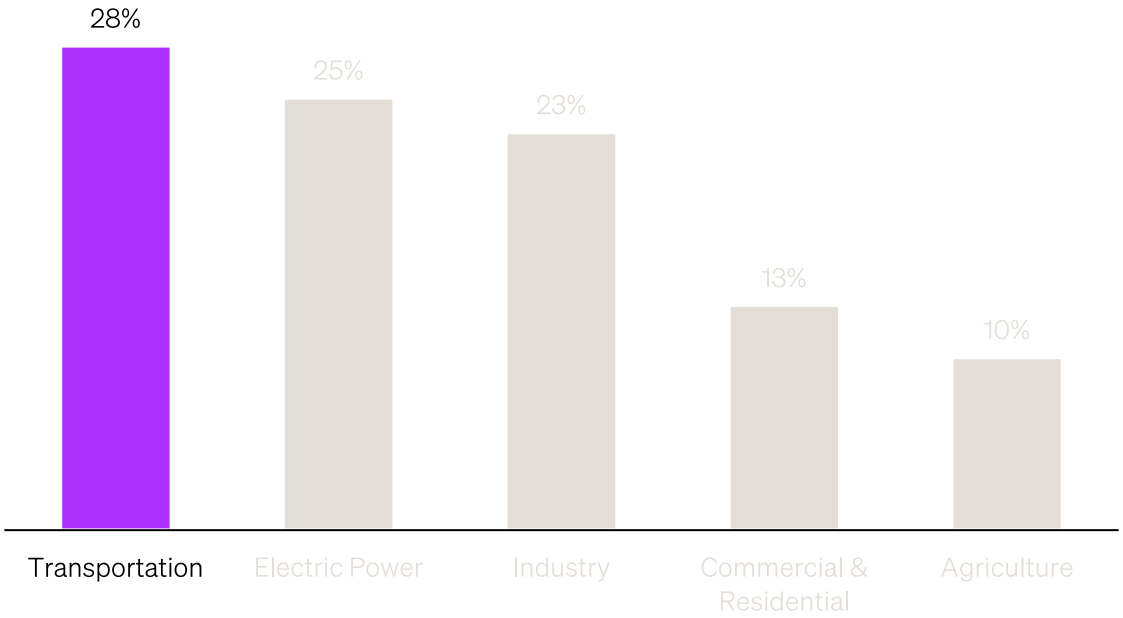
Source: EPA

CHAPTER 03

Decarbonizing transportation

Transportation is Responsible for 28% of U.S. Emissions

U.S. GHG Emissions by Source



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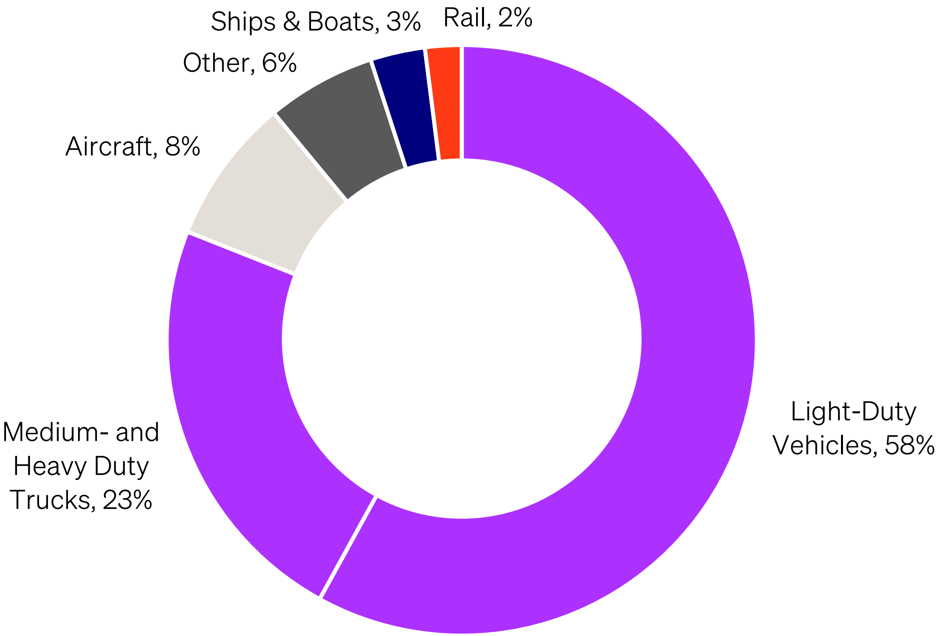
Source: EPA

Vehicle Emissions Dominate U.S. Transportation Sector Emissions

U.S. Transportation Sector GHG Emissions by Source, 2021



Source: EPA

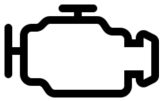
How do we decarbonize vehicles?

Battery and Plug-In Hybrid Electric Vehicle Engines Emit Fewer Emissions Than Internal Combustion Engines

Highest emissions → Lowest emissions

Internal Combustion Engine (ICE)

- Gasoline – the most common engine found in passenger vehicles
- Diesel – higher torque and fuel efficiency. Found in trucks and some passenger vehicles

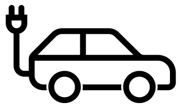


Plug-In Hybrid Electric Vehicle (PHEV)

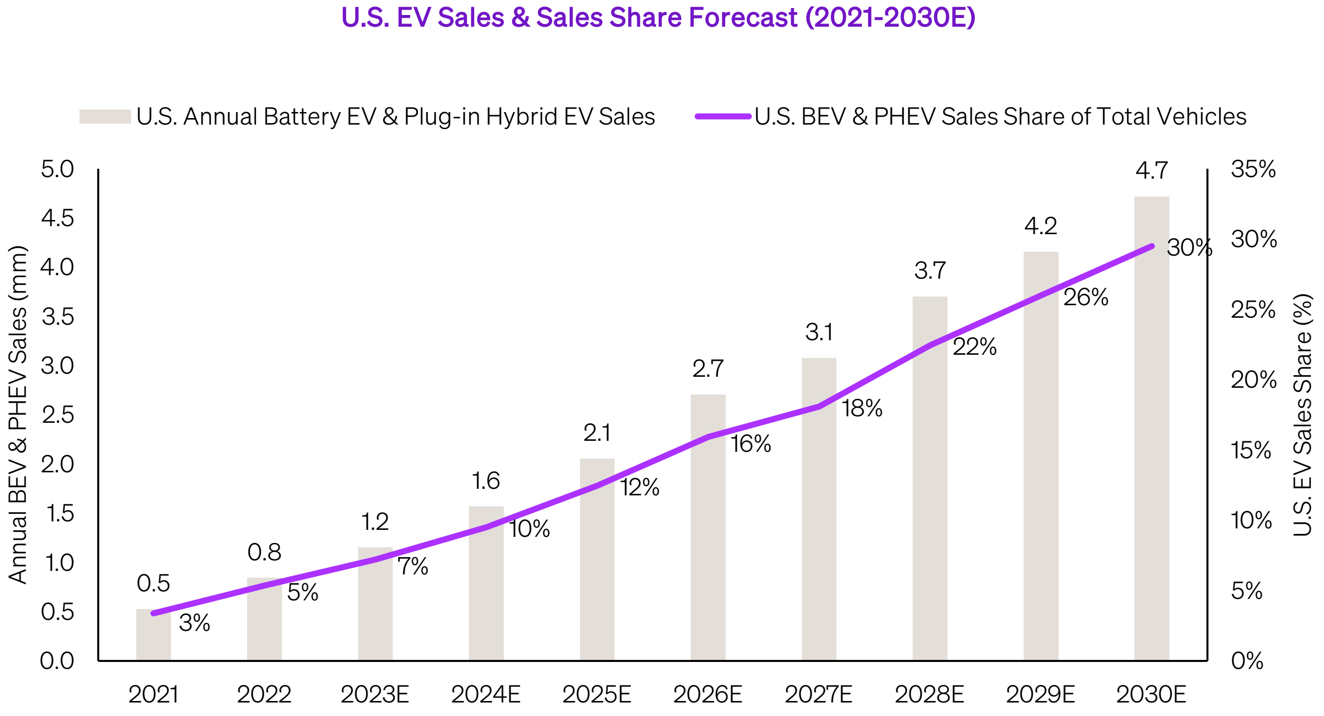
- Combining an internal combustion engine (ICE) with an electric motor and battery
- Can operate as electric-only, gasoline-only, or both to improve fuel efficiency and reduce emissions

Battery Electric Vehicle (BEV)

- All electric vehicle running entirely on electricity
- Powered by a large battery pack (typically lithium-ion)
- No internal combustion engine so no tailpipe emissions



EVs Can Replace Internal Combustion Engines For Transportation



But EV Batteries Have a Complex Supply Chain

EV Battery Supply Chain

Upstream → Midstream → Downstream → End of Life

Upstream

Mining of raw materials such as lithium, cobalt, manganese, nickel, and graphite

Challenges:

- Use of child and forced labor in mining and extraction
- Dangerous ore (tailings) disposal
- Water pollution and depletion

Midstream

Refining and processing to create active battery materials for cathode and anode

Challenges:

- China dominates processing of lithium, cobalt, graphite, and rare-earths
- Significant energy usage

Downstream

Assembly of battery cells into modules and sale to automakers for use in EVs

Challenges:

- China, South Korea and Japan dominate global battery manufacturing
- Significant energy usage

End of Life

Reuse and recycling

Challenges:

- Technically difficult to separate complex battery chemistry
- Safety concerns (fires)

Source: RMI

How do we decarbonize aviation?

Decarbonizing Aviation Using Lithium Batteries Faces Several Structural Challenges

Energy Density

- For the same amount of energy, lithium batteries are heavier and bulkier than diesel and kerosene
- Carrying enough batteries is often impractical due to space and weight constraints

Range

- Planes need to travel thousands of miles in a single journey
- It is often not feasible to carry enough batteries to cover these distances without requiring frequent recharging

Charging Infrastructure

- Charging planes would lead to significant downtime and lost revenue
- It would be costly and logistically challenging to build charging infrastructure at airports

Safety

- Hosting large quantities of lithium batteries can lead to fires and explosions
- “Thermal runaway” occurs when a hot battery breaks down, which accelerates the underlying reaction leading to uncontrollable heating

Source: National Renewable Energy Laboratory

Alternative Sources of Energy Can Be Processed to Produce Sustainable Aviation Fuel That Can Substitute For Fossil Fuels

Corn Grain & Other Seeds

Fats, Oils & Greases

Algae

Agricultural & Forestry Residues

Wood Mill Waste

Wet Waste Streams

Solid Waste Streams

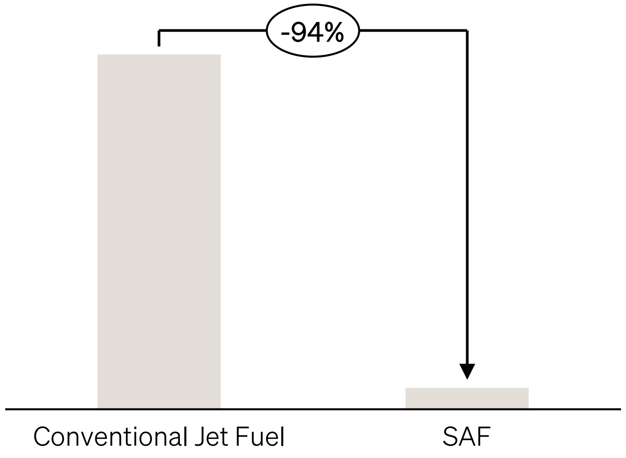
Dedicated Energy Crops

Source: Energy.gov

Sustainable Aviation Fuel Can Significantly Reduce Aircraft Emissions

Feedstock Collection	▪ Feedstocks like biomass, used cooking oils and municipal waste are collected and prepared for processing
Processing	▪ Biomass is converted to synthetic gas, which is a mixture of hydrogen and carbon monoxide ▪ Used cooking oils and fats are hyper-processed to produce hydrocarbons
Fuel Synthesis	▪ Synthetic gas is further processed to create long chain hydrocarbons ▪ Hydrocarbons from hyper-processing are further refined to meet aviation standards
Blending and Upgrading	▪ The output of this is sustainable aviation fuel, which is blended with conventional jet fuel and further refined to meet aircraft specifications

Compared with conventional jet fuel, 100% sustainable aviation has the potential to reduce greenhouse gas emissions by up to 94%



How do we decarbonize shipping?

Decarbonizing Shipping Using Lithium Batteries Faces Several Structural Challenges

Energy Density

- For the same amount of energy, lithium batteries are heavier and bulkier than diesel and kerosene
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- Charging ships would lead to significant downtime and lost revenue
- It would be costly and logistically challenging to build charging infrastructure at key ports

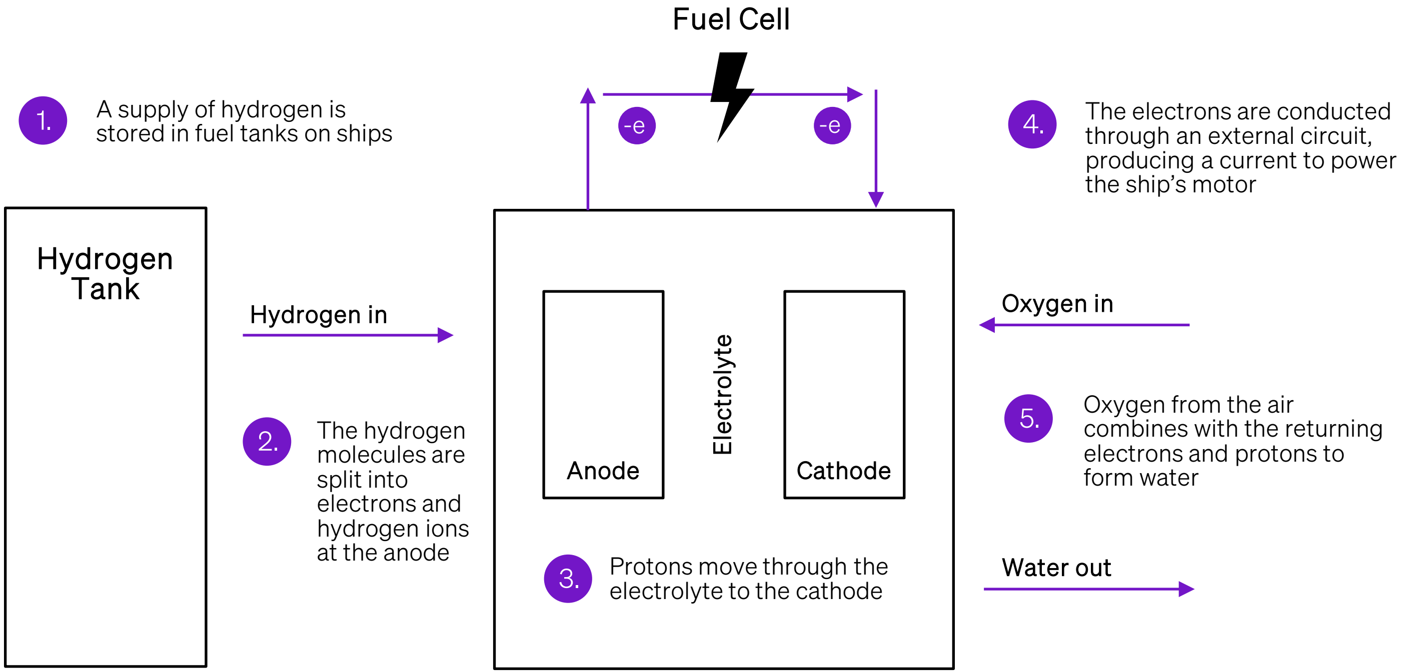
Safety

- Hosting large quantities of lithium batteries can lead to fires and explosions
- “Thermal runaway” occurs when a hot battery breaks down, which accelerates the underlying reaction leading to uncontrollable heating

Source: EVAdoption.com

Hydrogen Fuel Cells Can Replace Fossil Fuels to Decarbonize Shipping

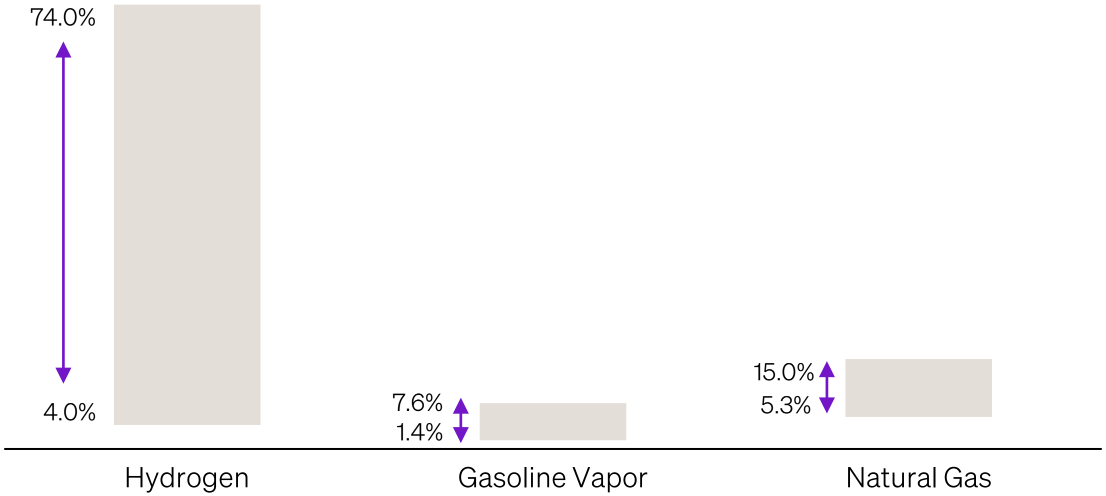
Hydrogen and oxygen react to produce electricity, water, heat, and no other emissions



Source: Fuel Cell & Hydrogen Energy Association

But Hydrogen Has a Wide Range of Flammable Concentrations in Air and Requires Less Energy to Ignite Than Gasoline or Natural Gas, Making it Dangerous if Handled Improperly

% Concentration Range Within Which Substance Can Ignite



Source: Department of Energy

Dive Deeper…

Further Reading & Watching

Reading:

- EV Sales Forecasts – EV Adoption
- The EV Battery Supply Chain Explained – Rocky Mountain Institute
- The Spiraling Environmental Cost of Our Lithium Battery Addiction – WIRED
- Hydrogen Safety – Department of Energy

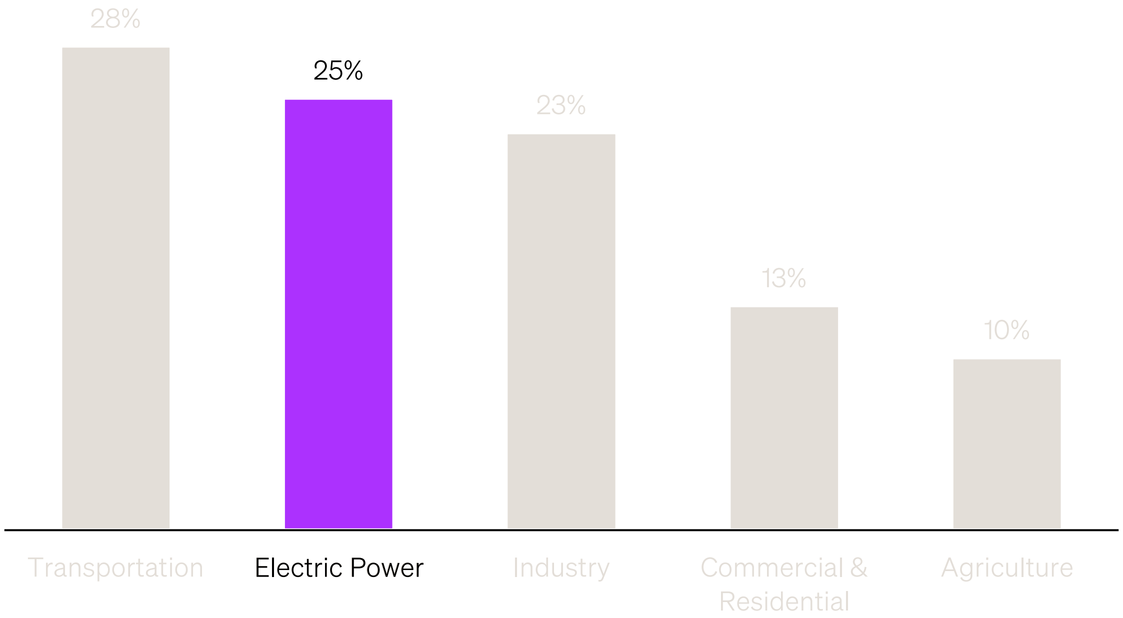
Watching:

- Electric Vehicles' Battery Problem – Wendover Productions
- What Is Green Hydrogen And Will It Power The Future? – CNBC
- How Do Hydrogen Fuel Cells Work? – Reactions
- How Jet Fuel Is Made From Trash – WSJ

CHAPTER 04

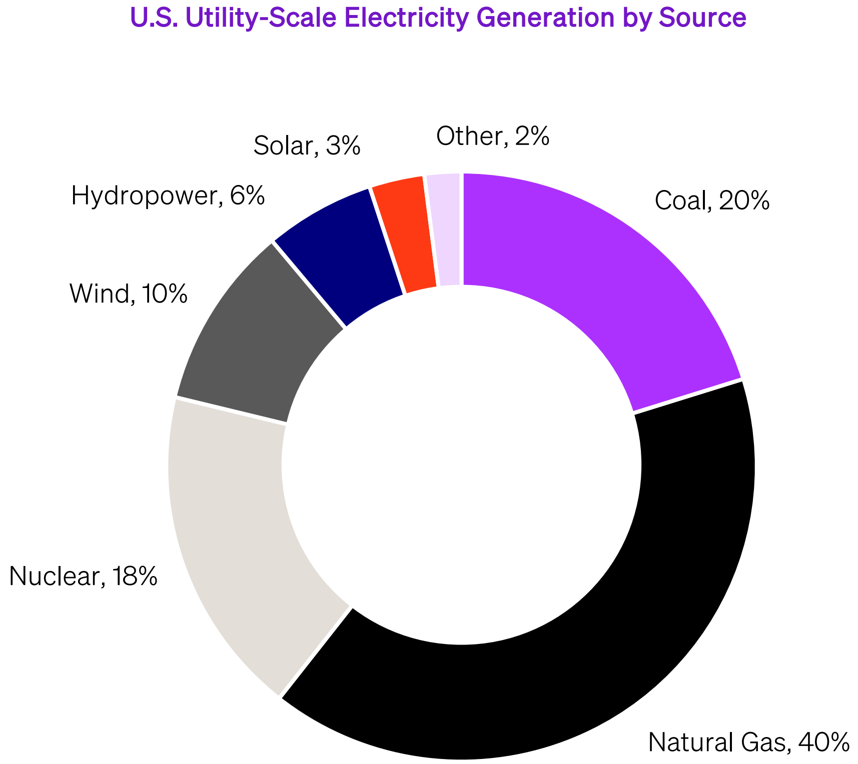
Decarbonizing power generation

Electric Power Generation is Responsible For 25% of U.S. Emissions



Source: EPA

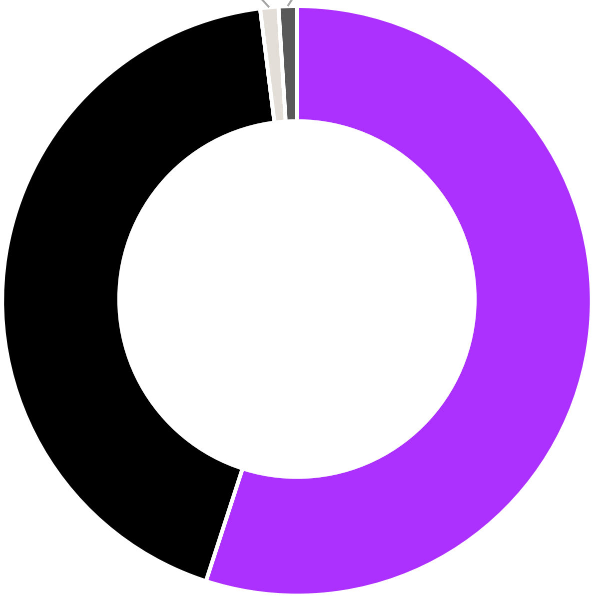
The U.S. Generates ~60% of its Electric Power From Coal and Natural Gas



Source: IEA

Which Are Responsible For ~98% of U.S. Power Sector Emissions

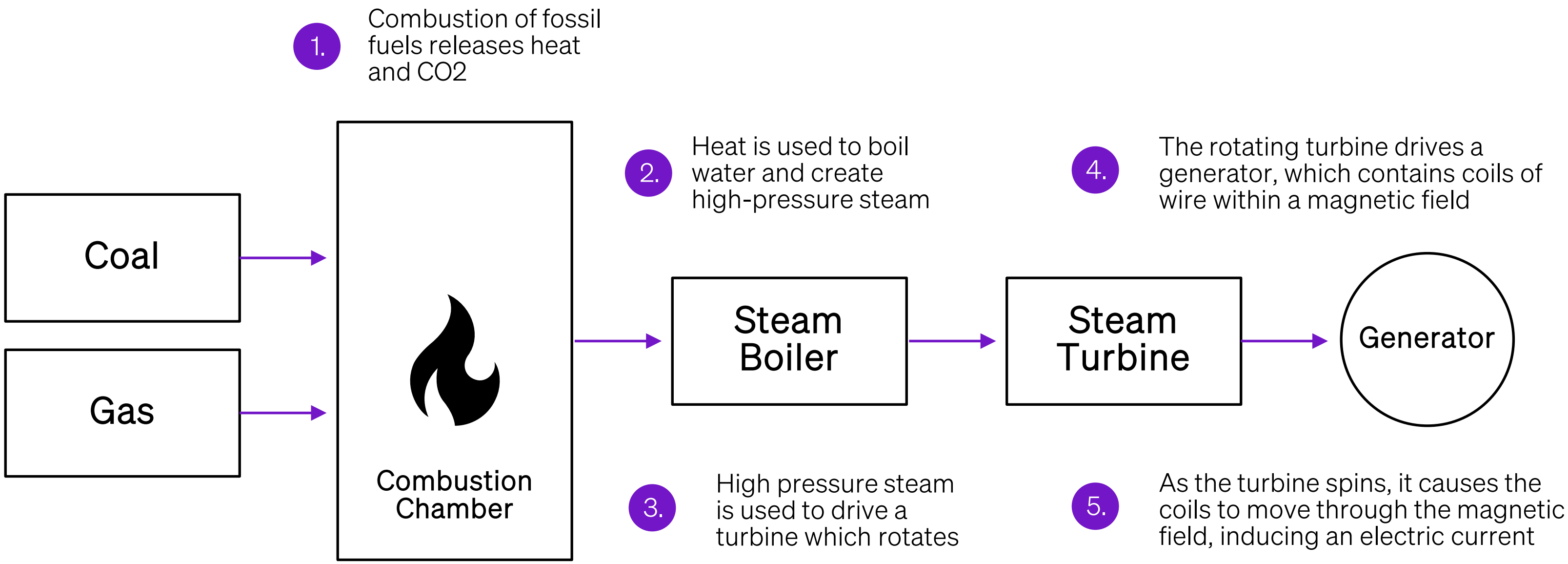
U.S. Power Sector GHG Emissions by Source, 2022



Source: IEA

How does burning coal and natural gas generate power?

Coal and Natural Gas Are Burned to Boil Steam, Which Drives a Generator



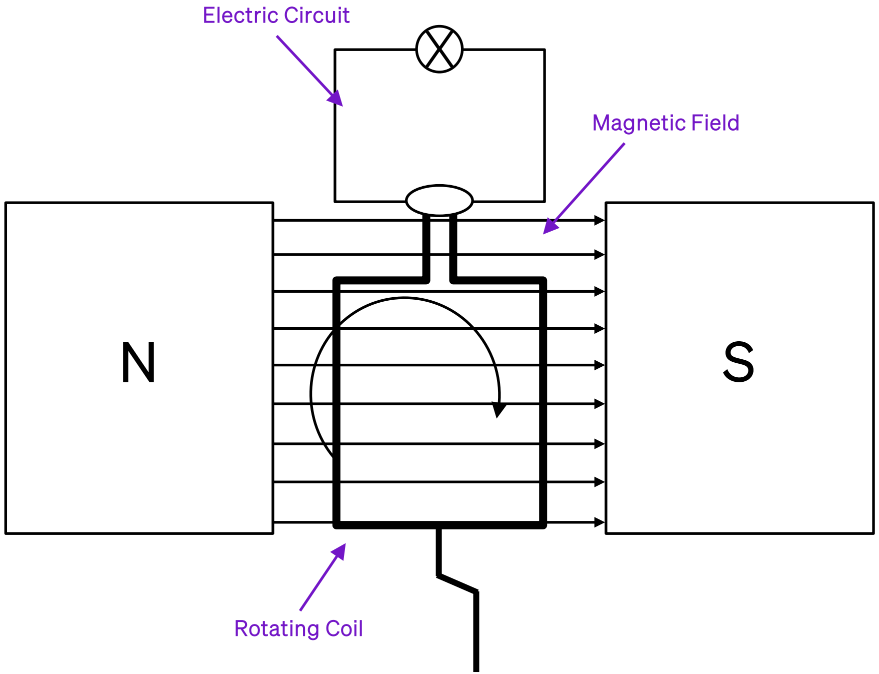
Source: Solar Power Guide

Generators Induce an Electric Current by Rotating a Wire Through a Magnetic Field

1. A coil of wire rotates within a magnetic field. This rotation is powered by a turbine which is driven by steam

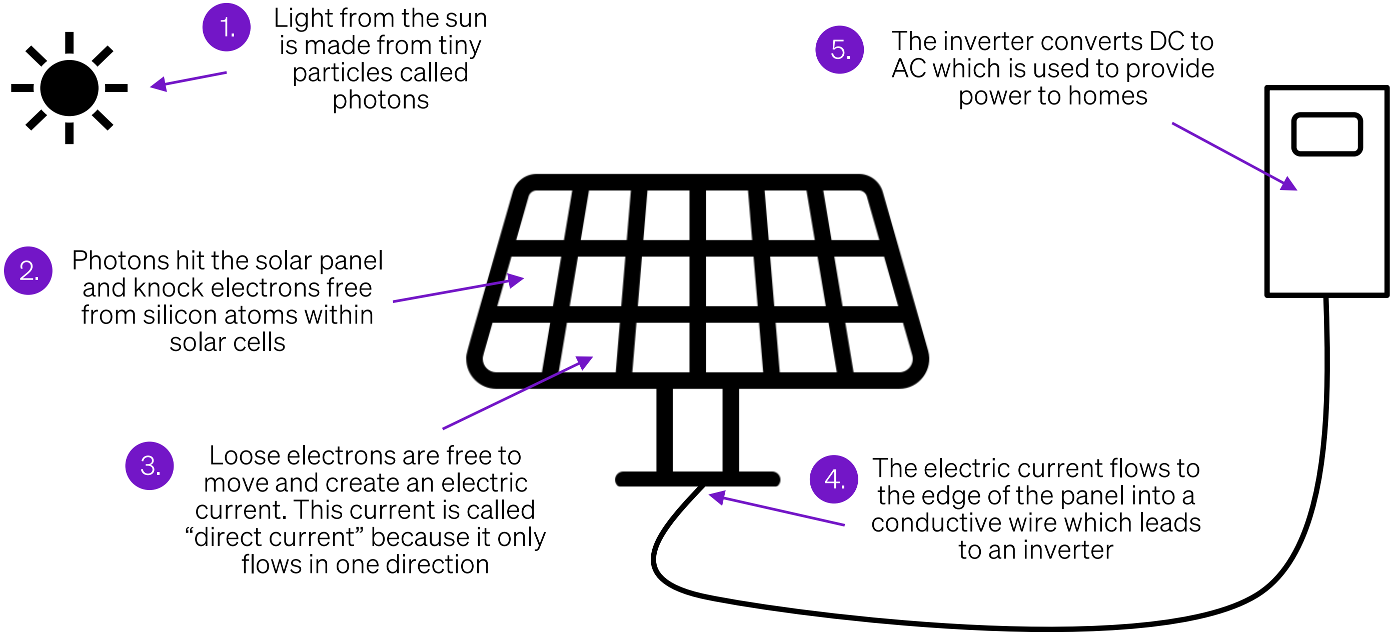
2. An electric current is “induced” in the coil as it cuts the magnetic field. An electric current is the flow of electrons (charged particles) in a specific direction

3. As the coil rotates, the direction in which it cuts the magnetic field lines changes, meaning that the direction of the induced current changes periodically. This is “alternating current”



Coal and natural gas can be replaced with renewable sources of power generation

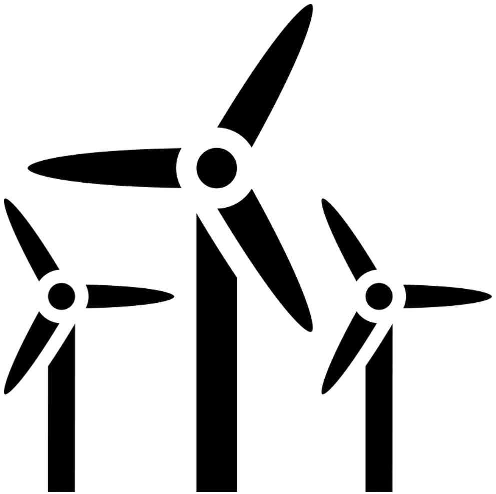
Solar Panels Can Convert Energy From the Sun into Electricity

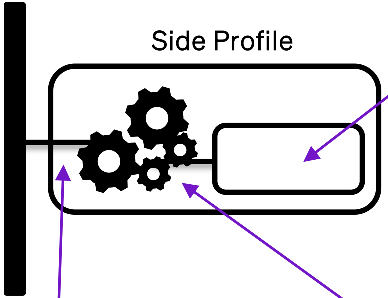


Source: Solar Power Guide

Wind Turbines Can Drive a Generator Using Energy From the Wind

1. The blades of a turbine catch the wind and rotate





2. As the blades rotate, they turn the rotor connected to the main shaft

3. This shaft transfers the rotational energy to the gearbox which increases the rotational speed

4. The high-speed rotation is transferred to the generator, where magnets spin within coils of wire, creating a flow of electrons

Source: Department of Energy

Dive Deeper…

Further Reading & Watching

Reading:

- How Electricity is Generated – EIA
- Where Does Our Electricity Come From? – World Nuclear Association
- Electric Power Sector Basics – EPA

Watching:

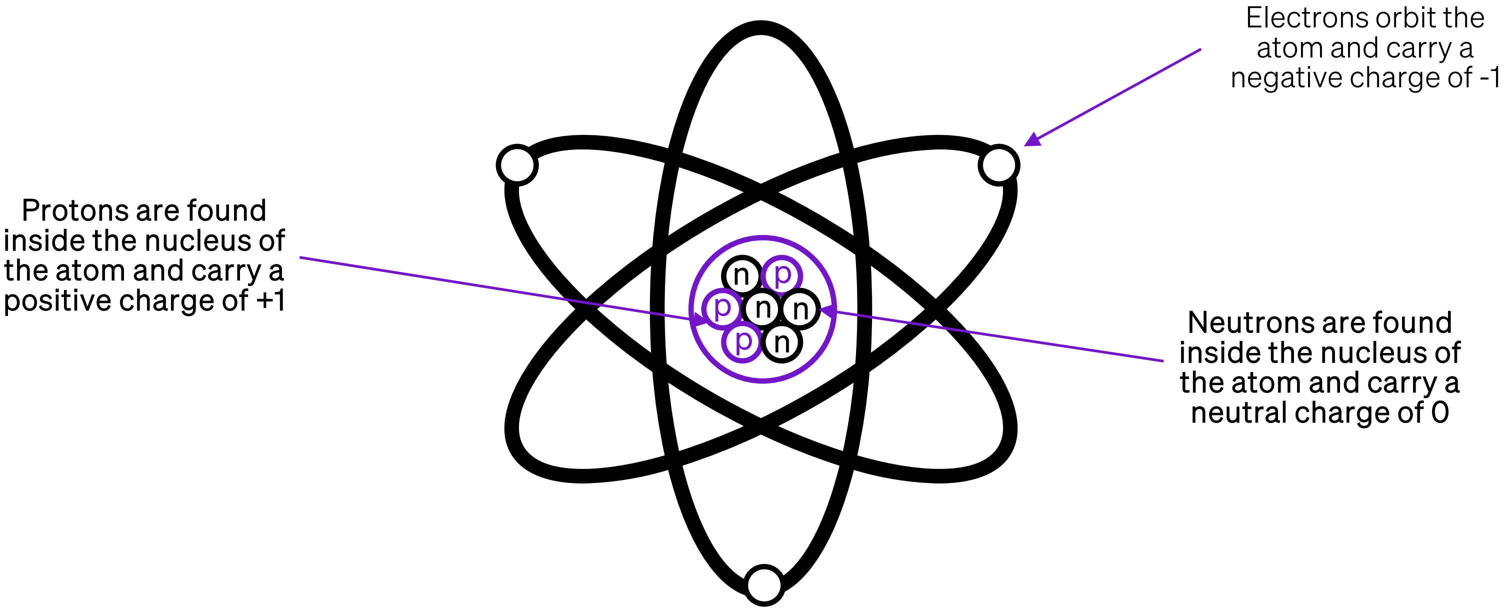
- How Do Coal Fired Power Stations Work? – LiacosEM
- How Do Solar Panels Work? – Ted Ed
- How Do Wind Turbines Work? – Lesics

Nuclear power is another emissions-free source of power generation

How does nuclear power work?

The Nucleus of an Atom Contains Protons and Neutrons

Model of an Atom

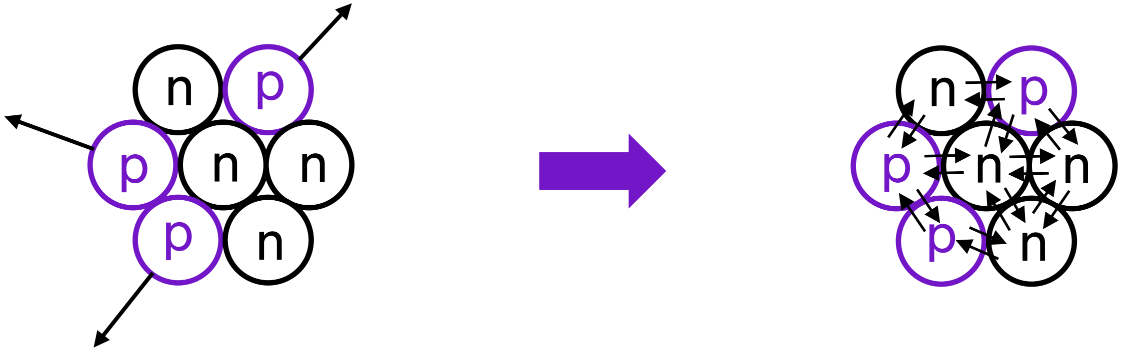


Source: EPA, Department of Energy

The Strong Nuclear Force Binds the Nucleus Together and Stores Energy

Protons with a like charge of +1 repel each other

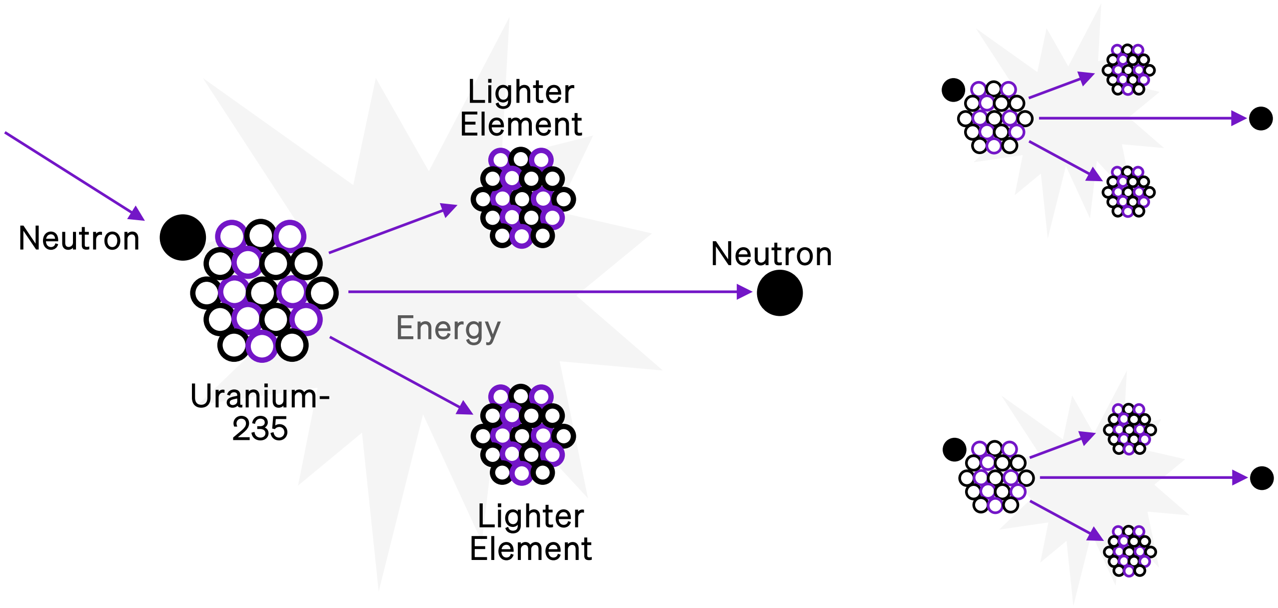
But the strong nuclear force holds the nucleus together



Source: Energy Education

Nuclear Fission Involves Firing a Neutron into an Unstable Nucleus, Which Splits Into Two to Release Energy

Fission also releases multiple neutrons which can continue the reaction as a chain



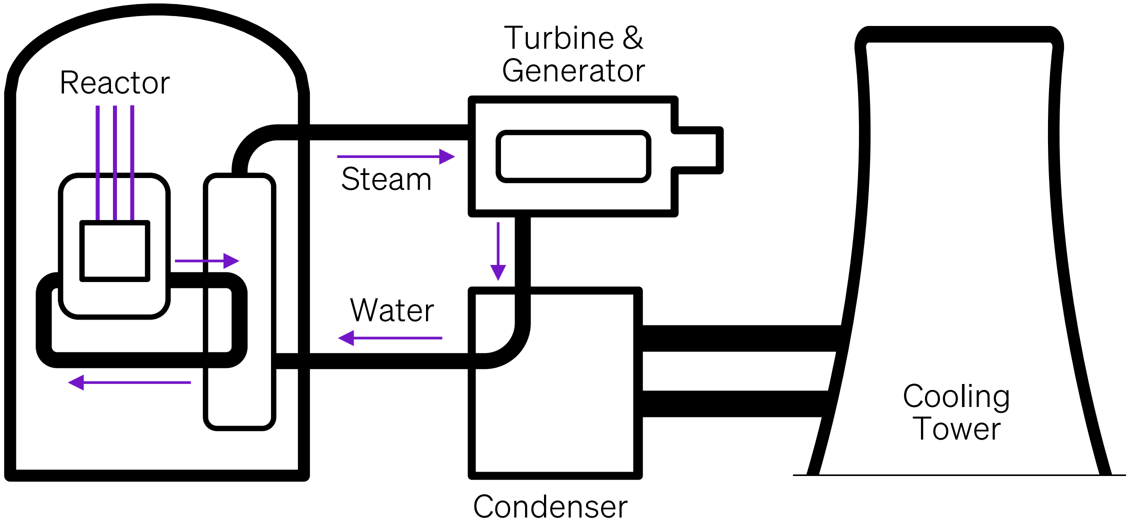
Source: MIT Nuclear Reactor Laboratory

Energy Released During Fission is an Emissions-Free Source of Heat, Which Can Be Used to Boil Steam and Drive a Generator

1. Fuel rods of uranium pellets are placed in water

2. Nuclear fission releases energy in the form of heat while releasing zero carbon emissions

3. This heat is used to boil water into high-pressure steam

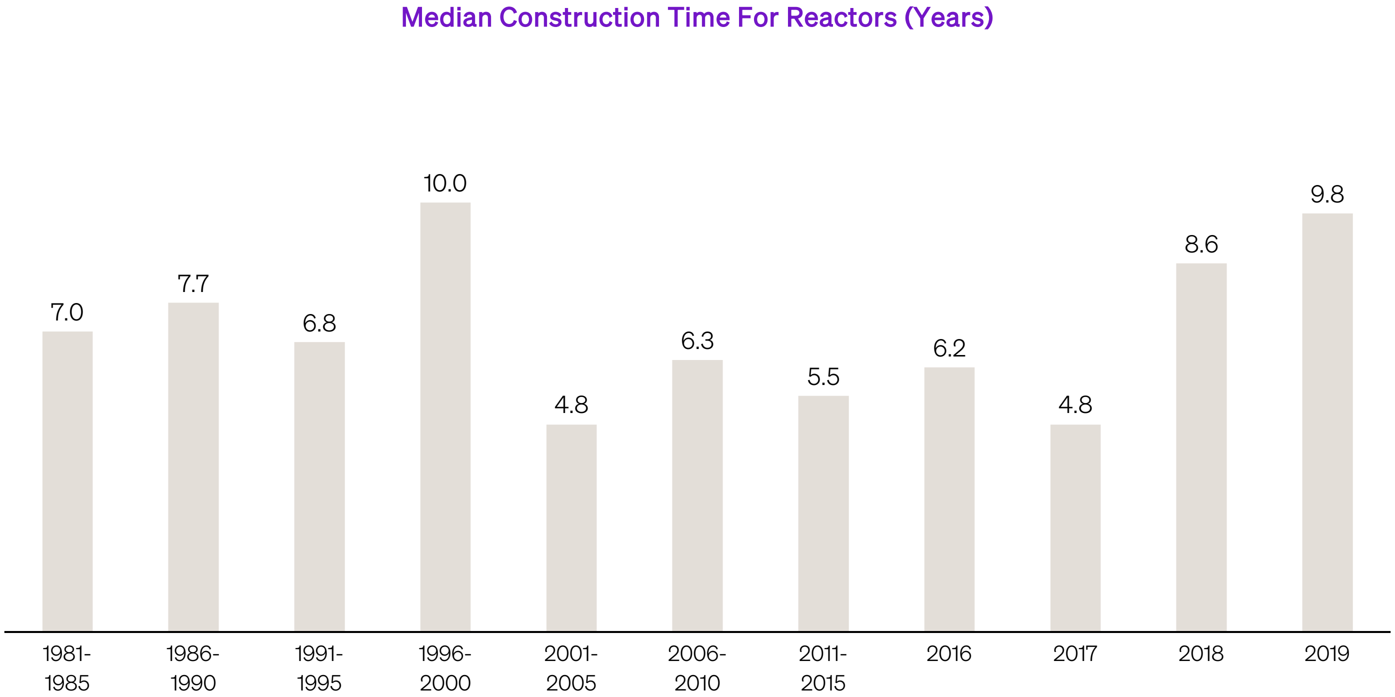


4. Steam moves through a turbine which drives a generator, inducing an electric current

5. The steam is cooled at a cooling tower, condenses back into water, and is subsequently reused

Source: EPA, Department of Energy

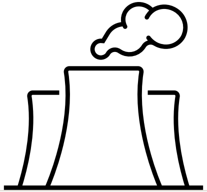
But Traditional Nuclear Power Plants Can Take Many Years to Construct



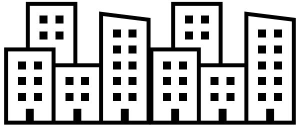
Source: World Nuclear Association

Small Modular Reactors and Microreactors Can Be Factory Assembled and Scaled to Locations Not Suitable for Traditional Nuclear Power Plants

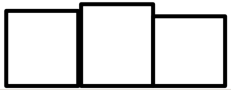
Large, Conventional Reactor
700+ MW



Located near a body of water, suitable for powering cities

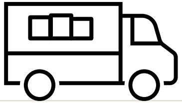


Small Modular Reactor
Up to 300 MW



Envisioned for remote areas with limited grid capacity

Microreactor
Up to ~10 MW



Suited for microgrids and industrial applications

Source: IAEA

Nuclear fusion is an evolving technology which replicates how stars produce energy, and could produce limitless clean energy if successful

How does nuclear fusion work?

Under Appropriate Conditions, the Energy of an Atom is Interchangable With its Mass

Einstein Mass-Energy Equivalence

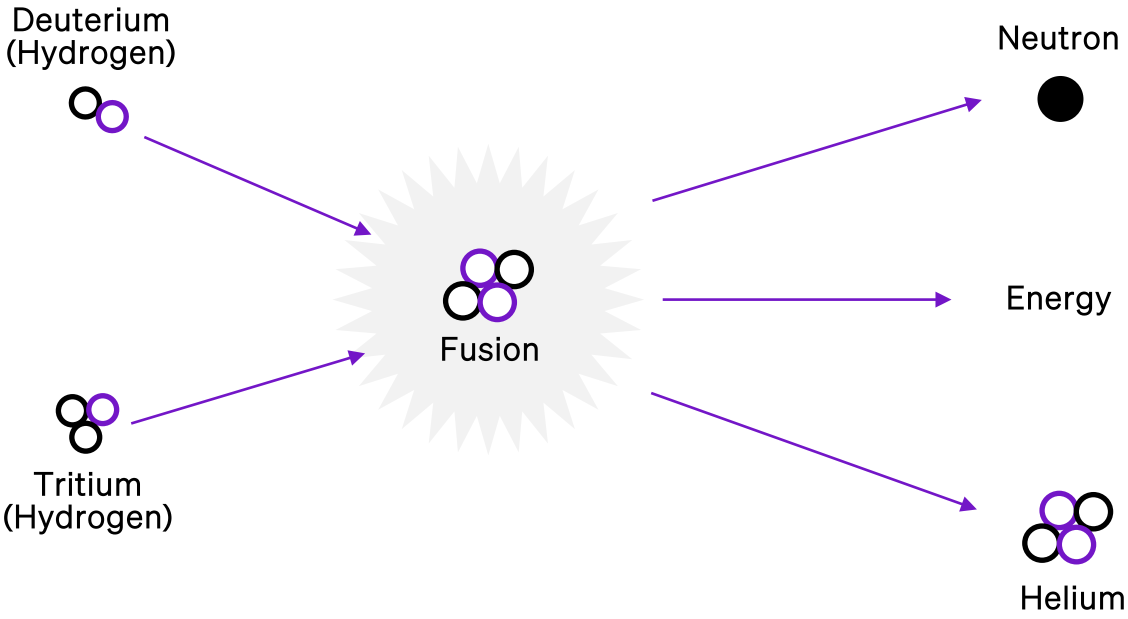
$$E = mc^2$$

Energy

Mass

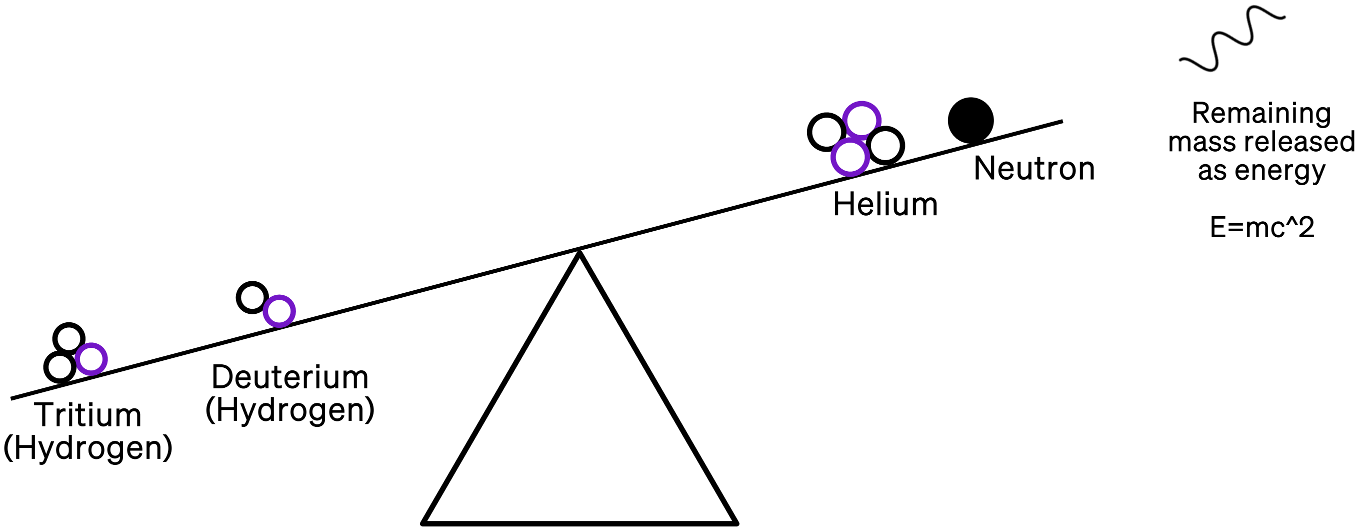
Speed of light squared

Nuclear Fusion Involves Merging Two or More Nuclei Together to Release Energy



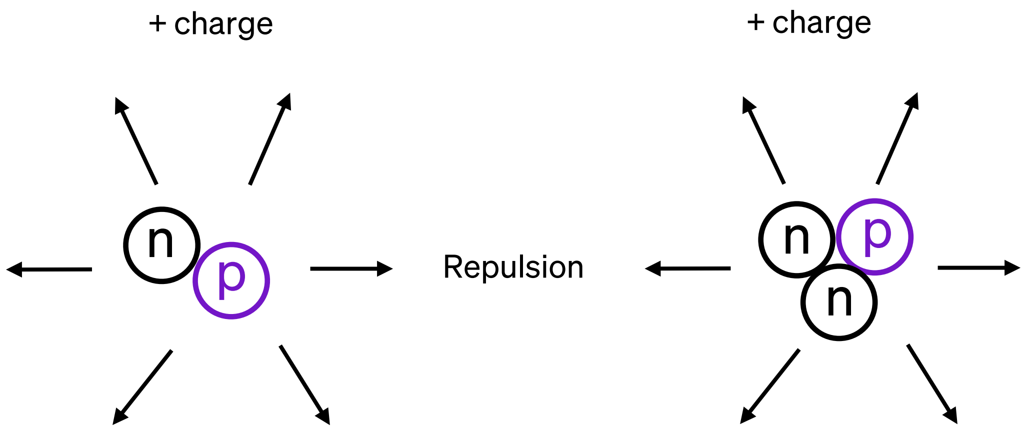
Source: Department of Energy

Since the Total Mass of the Fused Nucleus is Lower Than the Mass of the Two Original Nuclei, the Remaining Mass is Released as Emission-Free Energy



Source: Department of Energy, Astronomy Notes

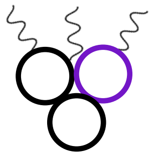
Normally, Fusion is Not Possible Due to the Repulsive Forces Between Two Nuclei Which Have Similar Charges



Magnetic Confinement Fusion Methods Heat Hydrogen to Become Plasma, and Use Magnetic Fields to Concentrate the Plasma to Initiate a Fusion Reaction

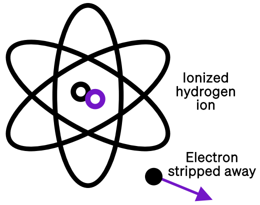
Tokamaks, Stellarators and Reversed Field Pinch Devices are Examples of Magnetic Confinement Fusion

1.



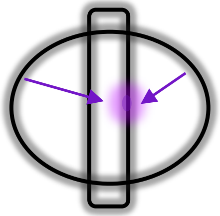
Deuterium and Tritium are heated to an extremely high temperature of 150,000,000°C using high-frequency waves

2.



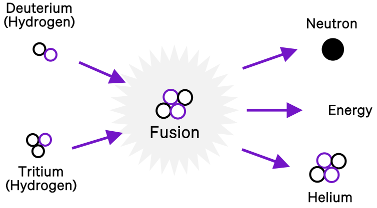
At these temperatures, the electrons are stripped away from the atoms, creating an ionized state of matter called plasma

3.



Large magnetic coils generate a powerful magnetic field which concentrates the charged particles away from the walls and in the center of the reactor

4.

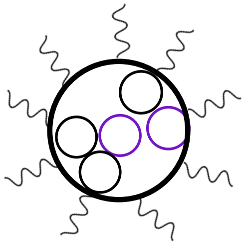


Once the plasma is confined, a fusion reaction begins between the deuterium and tritium to produce helium, releasing a neutron and energy

Source: ITER, World Nuclear Association

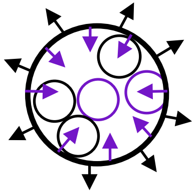
Inertial Confinement is a Developing Method of Fusion Which Focuses Laser Beams Onto a Pellet of Deuterium-Tritium Fuel, Which Implodes and Compresses to Initiate Fusion

1.



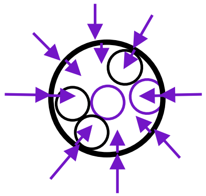
Laser beams or produced X-Rays heat the pellet, forming a surrounding plasma envelope

2.



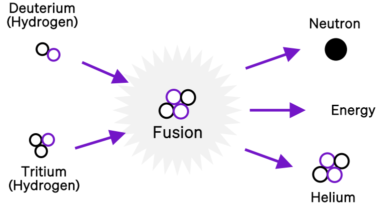
The outside of the capsule expands rapidly, causing the rest of the capsule to implode inwards per Newton's law that every action has an equal and opposite reaction

3.



During the final part of the implosion, the capsule reaches ~1,000x its original density and ~30,000,000°C

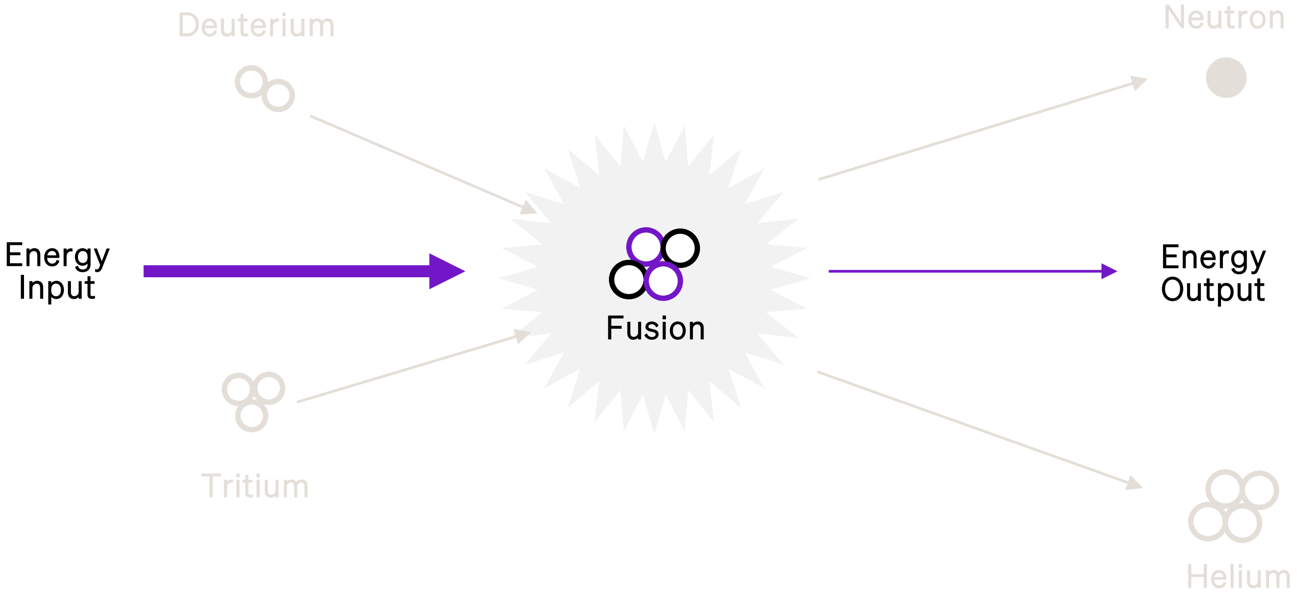
4.



Under these conditions nuclear fusion initiates, reaching a temperature of over a billion Celsius and releasing energy

Source: World Nuclear Association, University of York School of Physics

Currently, Fusion Technologies Require More Energy as Input Than They Release, Resulting in Net Energy Loss



Source: Department of Energy

Dive Deeper…

Further Reading & Watching

Reading:

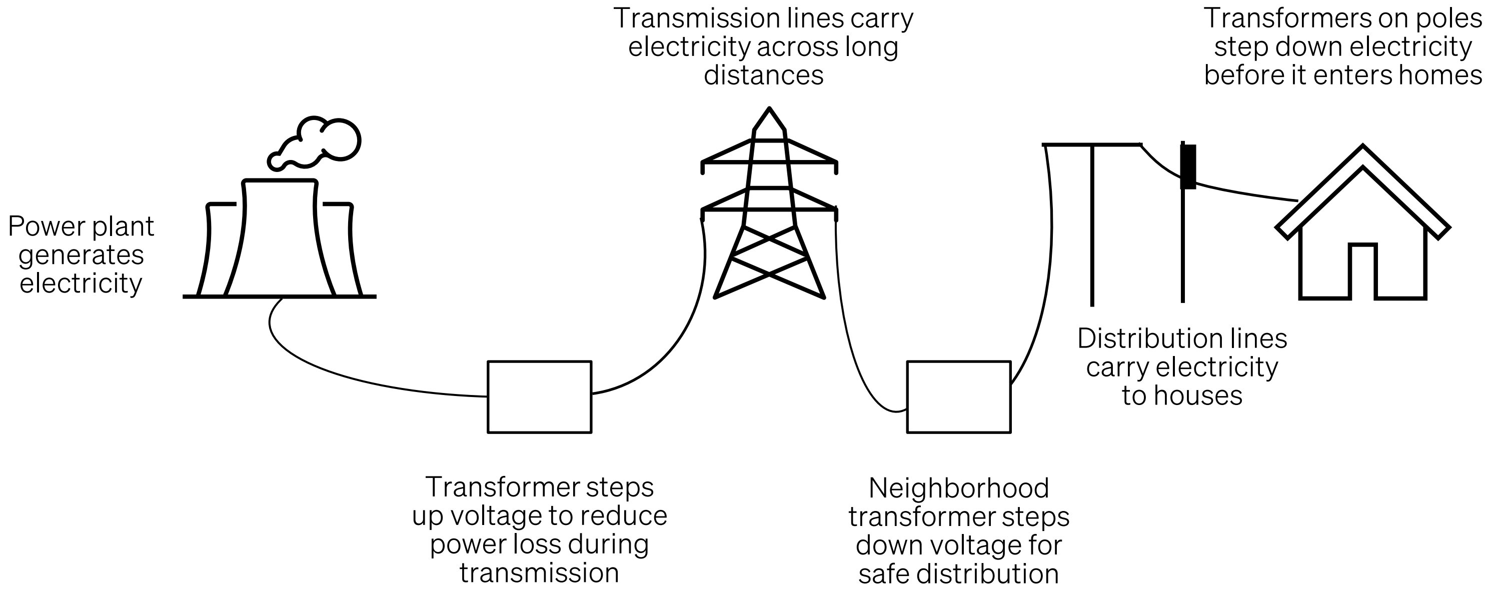
- Nuclear Power 101 – NRDC
- What is Fusion? – ITER
- Helion Energy – Helion Energy
- Nuclear Fusion Power – World Nuclear Association

Watching:

- Nuclear Physics: Crash Course Physics #45 – CrashCourse
- How Do Nuclear Power Plants Work? – TED-Ed
- Fusion Power Explained – Future or Failure? – Kurzgesagt
- Nuclear Reactions, Radioactivity, Fission and Fusion – Professor Dave Explains

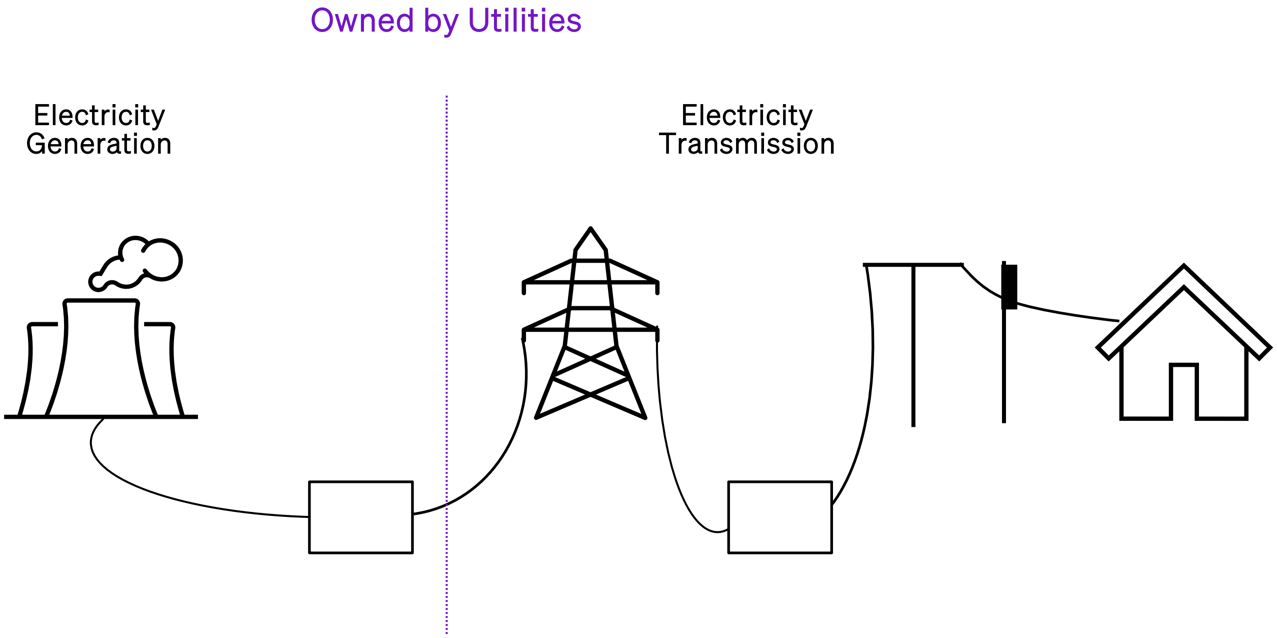
How does electricity reach your home?

Electricity Reaches the Home Through a Network of Transmission and Distribution Lines



Source: Energy Power Supply Association

Traditionally, U.S. Electricity Demand Was Primarily Served by Vertically Integrated Utilities Who Owned Both Electricity Generation and Transmission

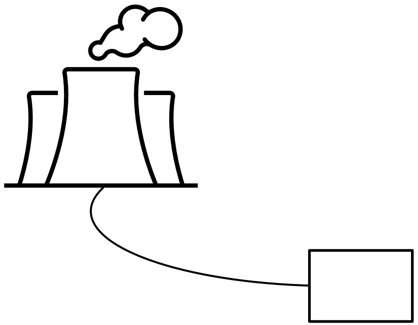


Source: Resources for the Future

But Since the 1990s, Many States Deregulated and Restructured Their Electric Systems by Splitting Power Generation and Transmission to Create Independent Energy Suppliers

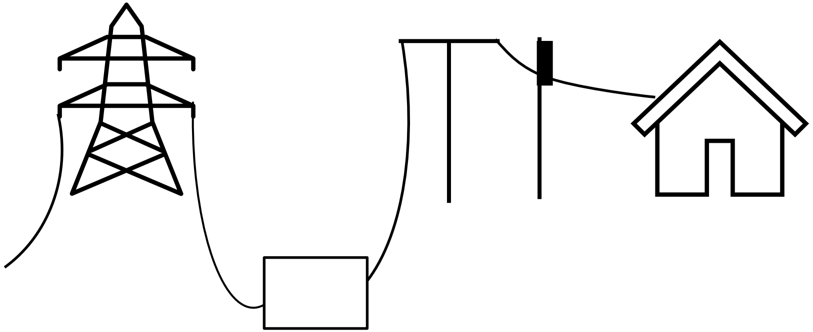
Independent Suppliers

Electricity
Generation



Owned by Utilities

Electricity
Transmission

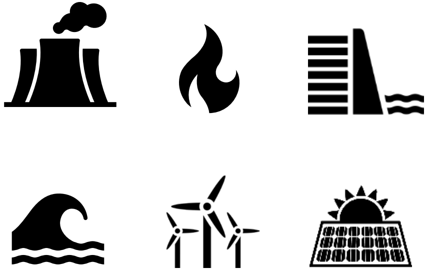


Source: Resources for the Future

This Created Competition For Customers, Who Could Now Choose From a Range of Electric Suppliers Instead of Just Their Local Utility

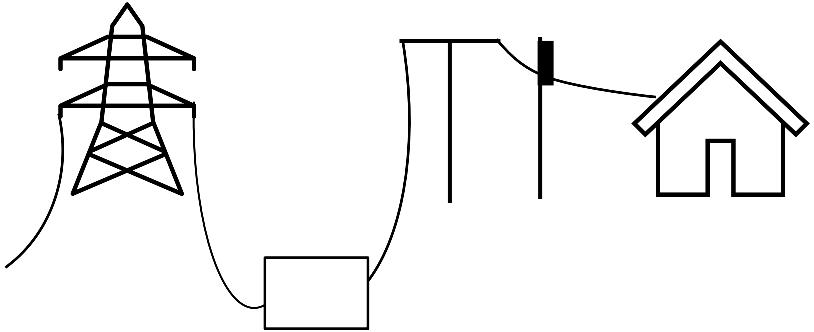
Independent Suppliers

Electricity Generation

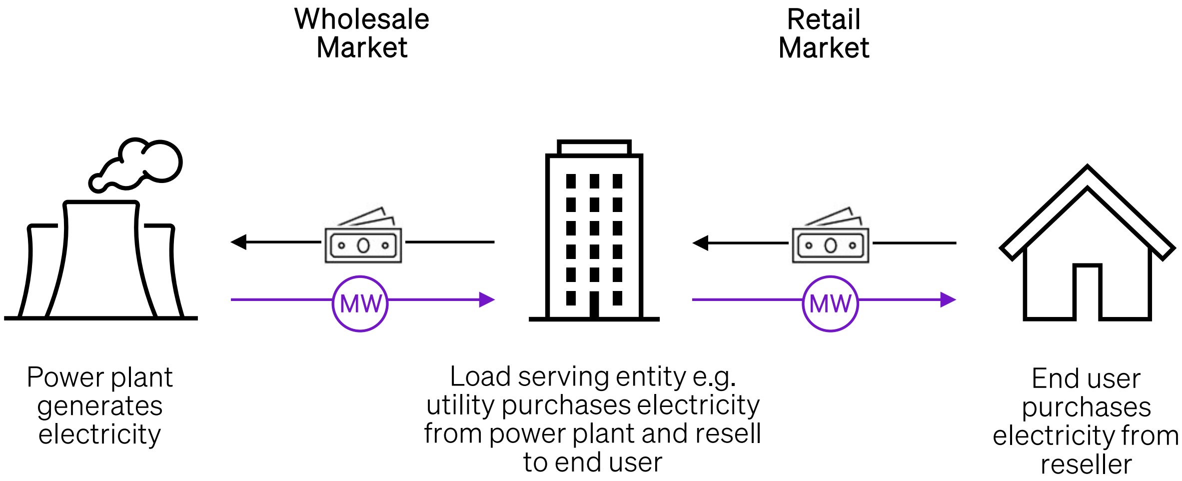


Owned by Utilities

Electricity Transmission



In Deregulated Markets, Electric Utilities Purchase Electricity From Power Generators at Wholesale Market Prices, and Resell Electricity to Consumers at Retail Market Prices

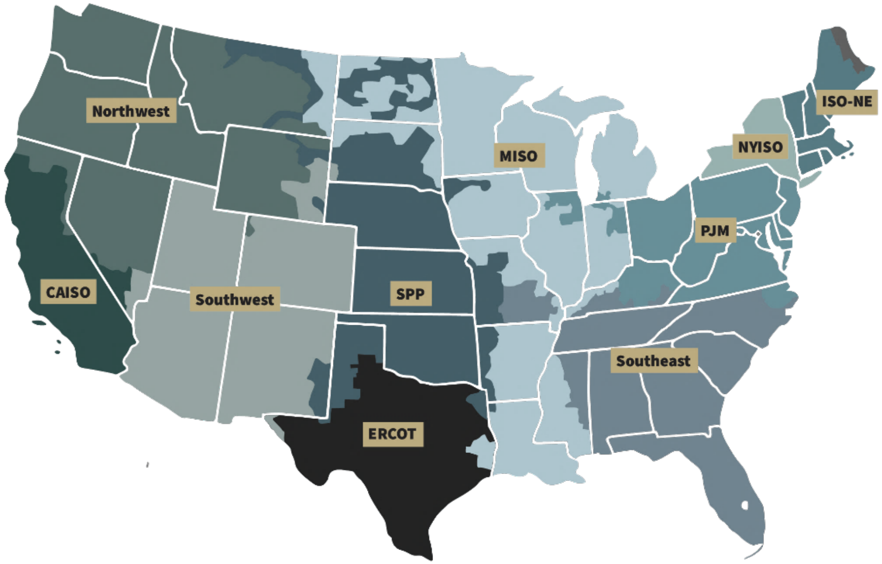


Source: PJM Learning Center, Resources for the Future

How do power markets work?

Regional Transmission Organizations (RTOs) and Independent System Operators (ISOs) Operate Electricity Grids and Manage Wholesale Power Markets Across Regions

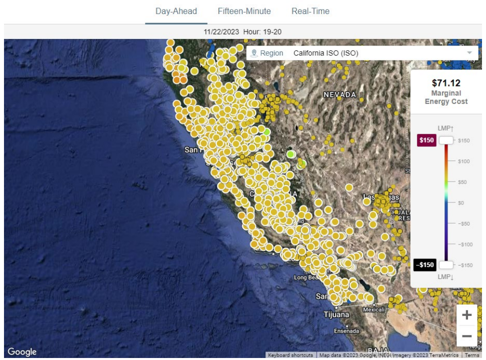
Map of RTOs and ISOs



RTOs and ISOs Receive Bids From Utilities and Power Plants to Buy and Sell Electricity Over Different Time Periods

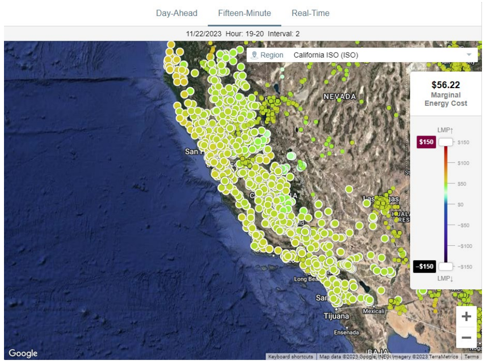
1. Day-Ahead Market

Represents ~95% of energy transactions based on forecasted load for next day



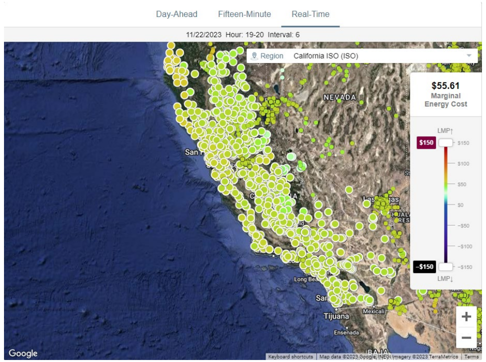
2. Fifteen-Minute Market

Market runs in 15-minute intervals to balance last-minute demand needs



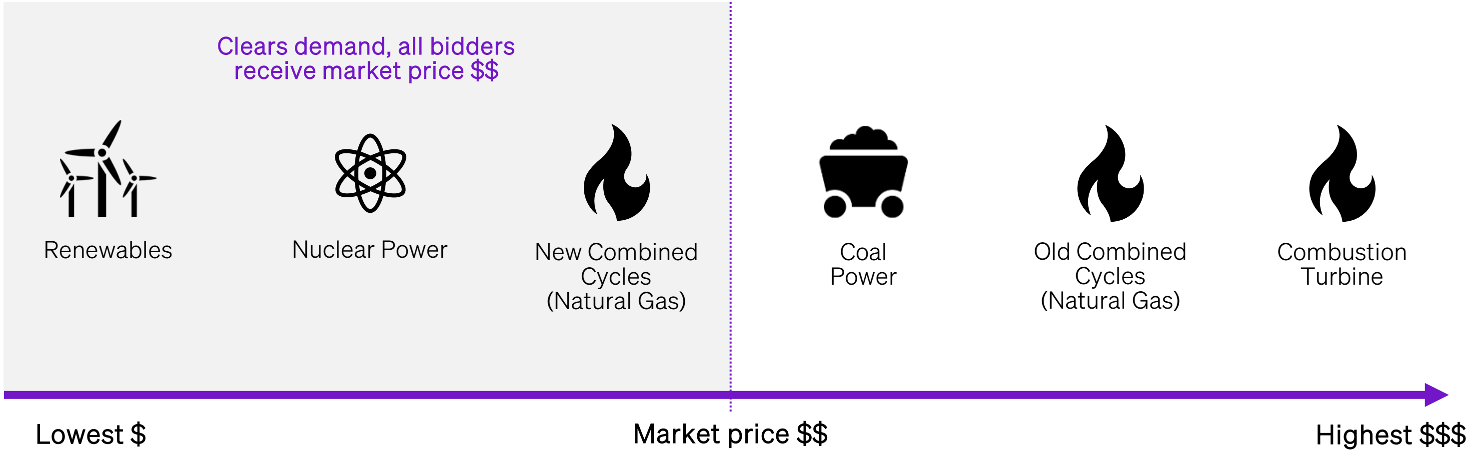
3. Real-Time Market

Market runs in 5-minute intervals to fine-tune balance between supply and demand



They Match These Bids by Organizing the Dispatch of Power in Order of Lowest to Highest Cost of Generation Until Their Region's Demand is Met

All bidders receive the market price, which is set by the marginal bid needed to meet demand



After Purchasing Power From the Wholesale Market, Utilities Charge Consumers Through a Monthly Bill Based Upon the Kilowatt Hours (kWh) of Electricity Consumed

Example Electricity Bill

EVERSOURCE

Account Number: 0000 000 0000
Customer name key: CUST
Statement Date: 04/05/19
Service Provided To:
JOHN J CUSTOMER

Service Address: ANY STREET
ANY TOWN, MA 00000
Rate: A1 R1 RESIDENTIAL Bill Cycle: 03
Service from 03/07/19 - 04/03/19 27 Days
Next read date on or about: May 06, 2019

Meter Number	Current Read	Previous Read	Current Usage	Reading Type
0000000	30596	30143	453	Actual

Electricity priced on monthly kWh used

Monthly kWh Use

Apr	May	Jun	Jul	Aug	Sep	Oct
463	427	459	439	559	1035	559
Nov	Dec	Jan	Feb	Mar	Apr	
525	562	522	677	520	453	

Total Amount Due by 04/30/19 $117.17

Electric Account Summary	
Amount Due On 04/05/19	$133.48
Last Payment Received On 04/04/19	-$133.48
Balance Forward	$0.00
Current Charges/Credits	
Electric Supply Services	$61.55
Delivery Services	$55.62
Total Current Charges	$117.17
Total Amount Due	$117.17

Total Charges for Electricity

Supplier (Eversource) (Basic Svc Fixed)		
Generation Service Charge	453 kWh X .13588	$61.55
Subtotal Supplier Services		$61.55
Delivery (Rate A1 R1 RESIDENTIAL)		
Customer Charge		$7.00
Distribution Charge	453 kWh X .06396	$28.97
Transition Charge	453 kWh X -.00052	-$0.24
Transmission Charge	453 kWh X .02585	$11.71
Revenue Decoupling Charge	453 kWh X -.00057	-$0.26
Distributed Solar Charge	453 kWh X .00088	$0.40
Renewable Energy Charge	453 kWh X .00050	$0.23
Energy Efficiency	453 kWh X .01725	$7.81
Subtotal Delivery Services		$55.62
Total Cost of Electricity		**$117.17**
Total Current Charges		**$117.17**

Electric Power is Measured in Watts, Which Are Units of Energy (Joules) Used Per Second

Watts (W)
Lightbulb

- 1 watt = 1 joule of energy per second
- A 10-watt bulb uses 10 joules of energy per second

Kilowatts (kW)
Appliance

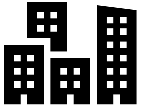
- 1 kilowatt = 1,000 joules of energy per second
- A 1.5kW electric kettle uses 1,500 joules of energy per second

Megawatts (MW)
Town

- 1 Megawatt = 1,000,000 joules of energy per second
- A 1MW wind turbine produces enough energy to power ~750 homes at any instant

Gigawatts (GW)
City

- 1 Gigawatt = 1,000,000,000 joules of energy per second
- The Hoover Dam has a generation capacity of ~2GW, enough to power ~1.5 million homes at any instant



Source: California ISO

1 kWh Represents 1 kW of Power Used for 1 Hour

Electrical Energy Usage is Measured as Watts Used Over a Period of Time

Watt Hours (Wh)
Lightbulb

- 1 watt hour = 1 watt device used for 1 hour
- A 10-watt bulb used for 2 hours = 20-watt hours

Kilowatt Hours (kWh)
Appliance

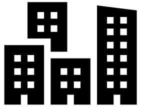
- 1 kilowatt hour = 1,000-watt device used for 1 hour
- A 1.5kW electric kettle used for 3 hours = 4.5kWh

Megawatt Hours (MWh)
Town

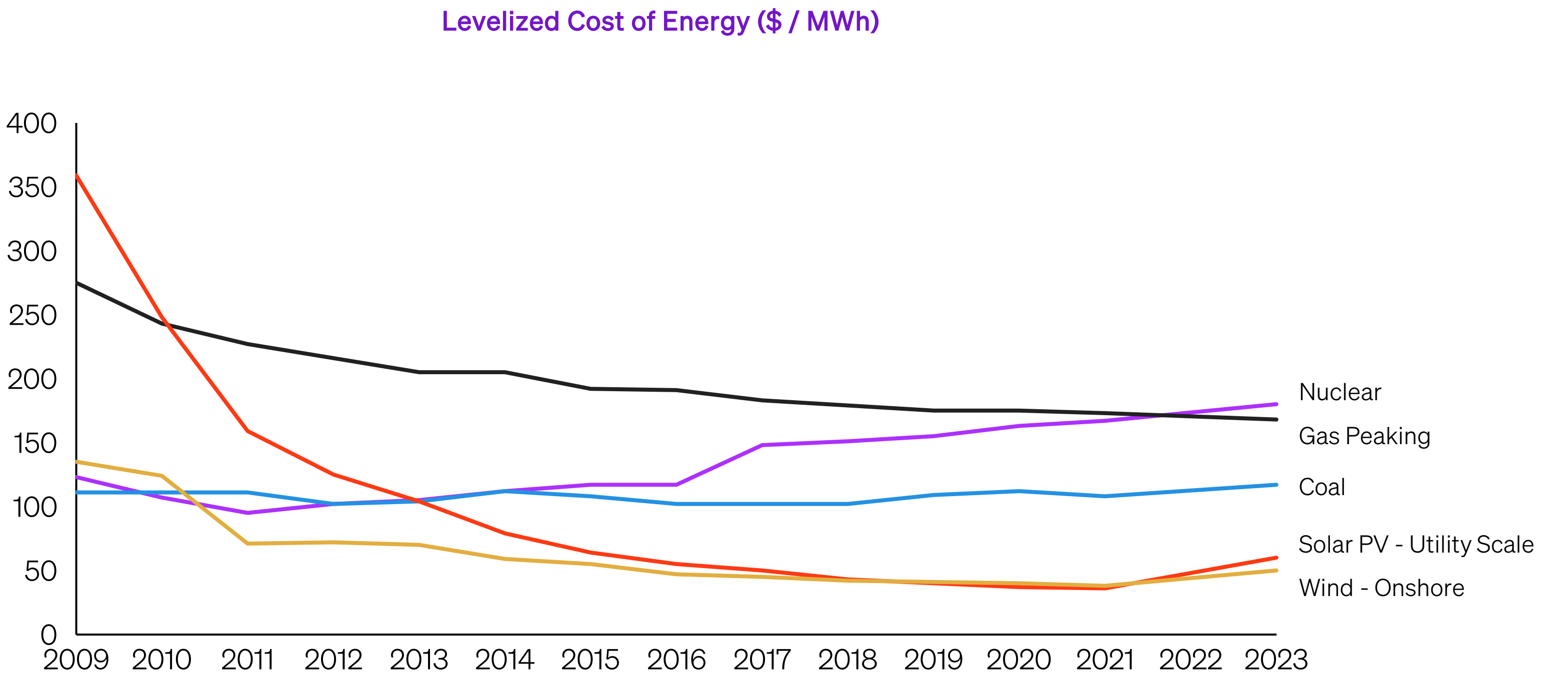
- 1 Megawatt hour = 1,000,000-watt device used for an hour
- A 1MW wind turbine rotating for 6 hours = 6MWh of electricity production

Gigawatt Hours (GWh)
City

- 1 Gigawatt hour = 1,000,000,000-watt device used for an hour
- A city that consumes 1GW at any instant = 24GWh of electricity consumed a day

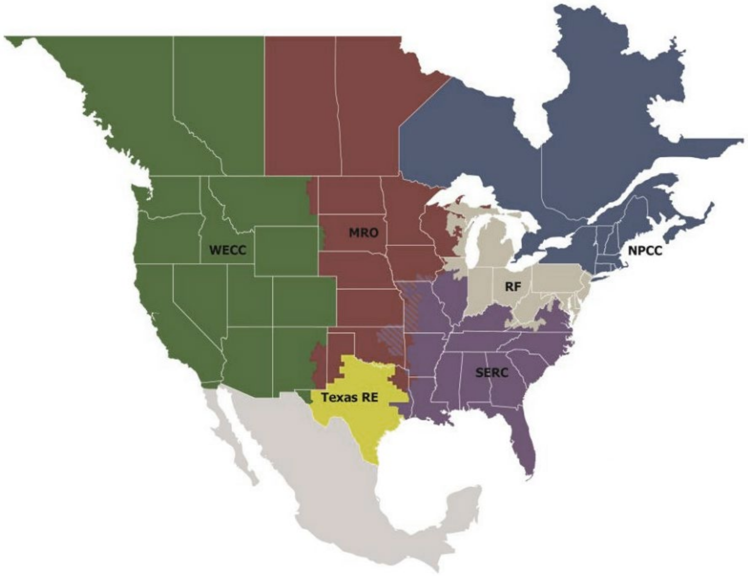


Solar and Wind Are Renewable Sources of Power Generation Which Offer the Lowest Levelized Cost of Energy Per MWh



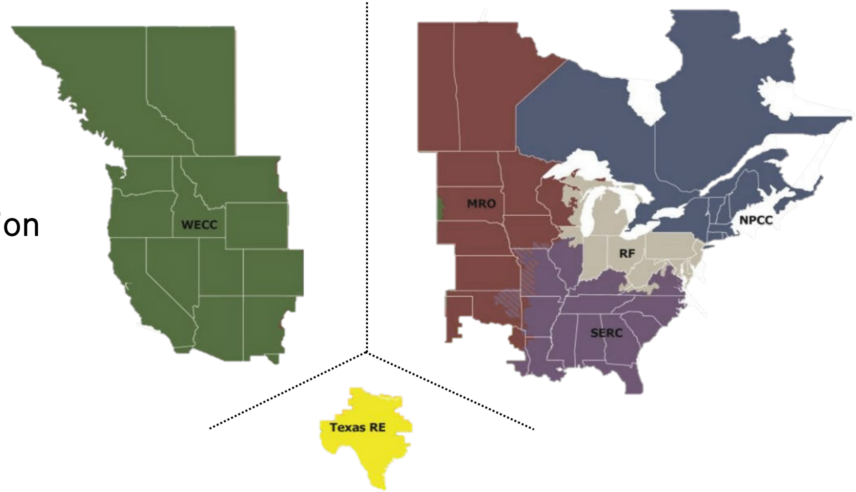
But adding renewable energy sources to the grid presents several key risks

The U.S. Grid is a Network of Power Plants, Transmission Lines, and Distribution Centers that Generate and Distribute Electricity



It is Divided into Three Major Regions Which Consist of Locally Interconnected Electricity Grids

Western Interconnection

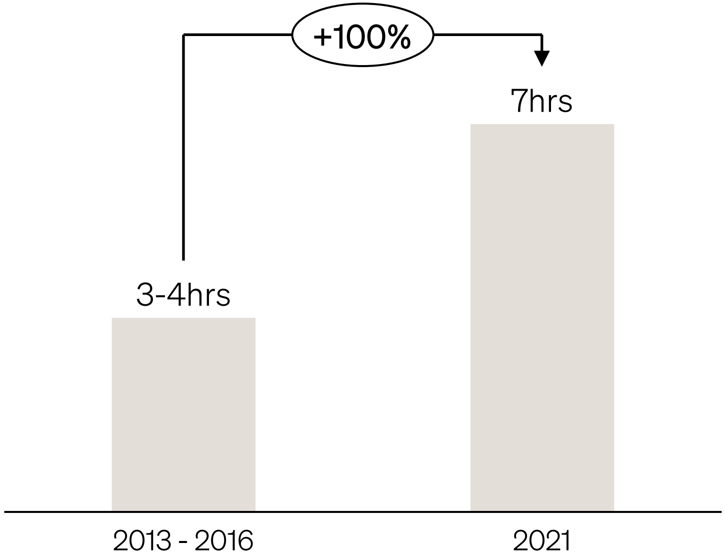


Eastern Interconnection

Texas Interconnected System

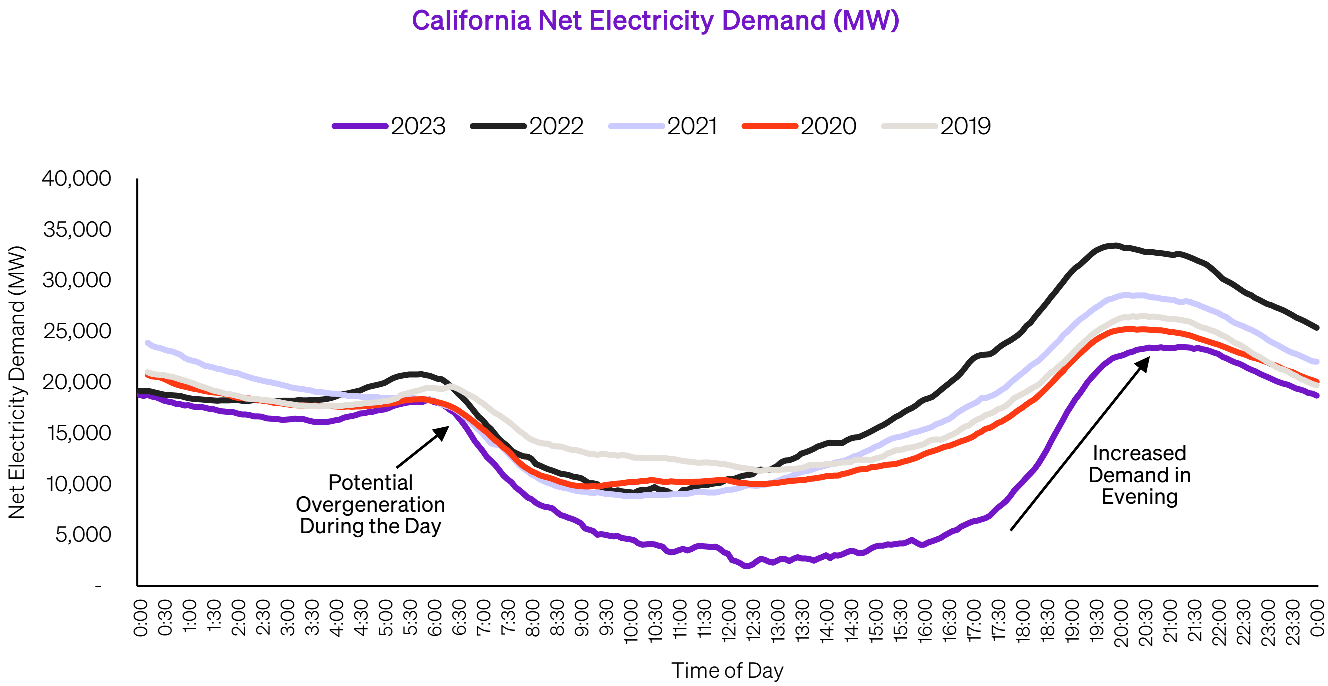
Extreme Weather and Rising Demand Are Threatening the Resiliency of Existing Grid Infrastructure, Which Was Mostly Built During the 1960s and 1970s

The average duration of a U.S. power outage has doubled in the last decade

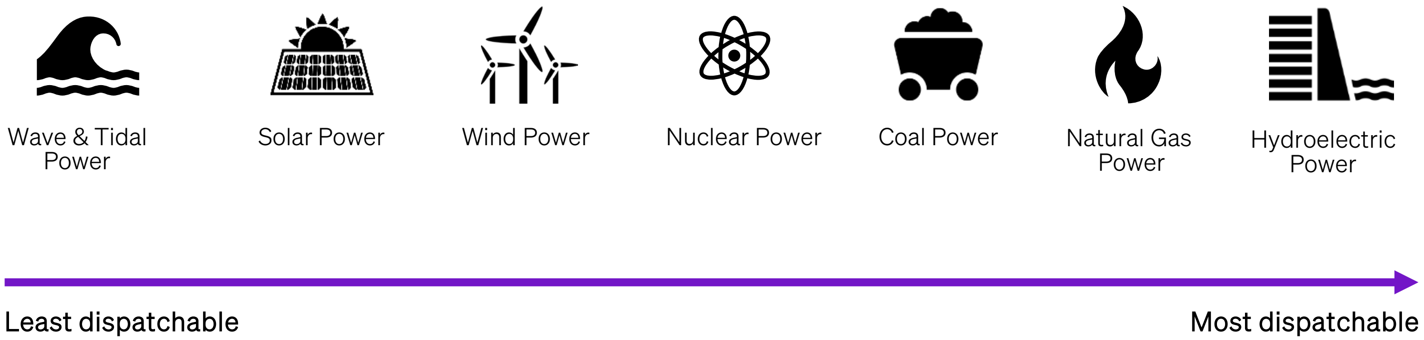


Source: CNBC, EPA

Adding Renewable Energy Sources Risks Oversupplying the Grid During the Day When Energy Demand is Lower, Resulting in Wasted Power Generation



And Many Renewables Cannot be Dispatched to Respond to Changes in Electricity Demand in the Same Way That Fossil Fuels Can

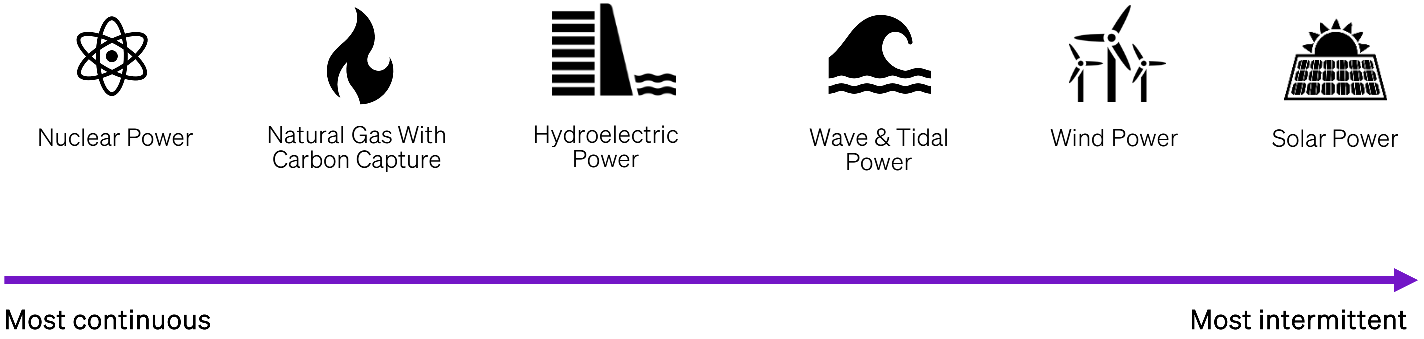


Source: Department of Energy

How do we build a carbon-free grid that can continue to provide power reliably?

A Wide Range of Energy Sources Can Generate Electricity Without Interruption

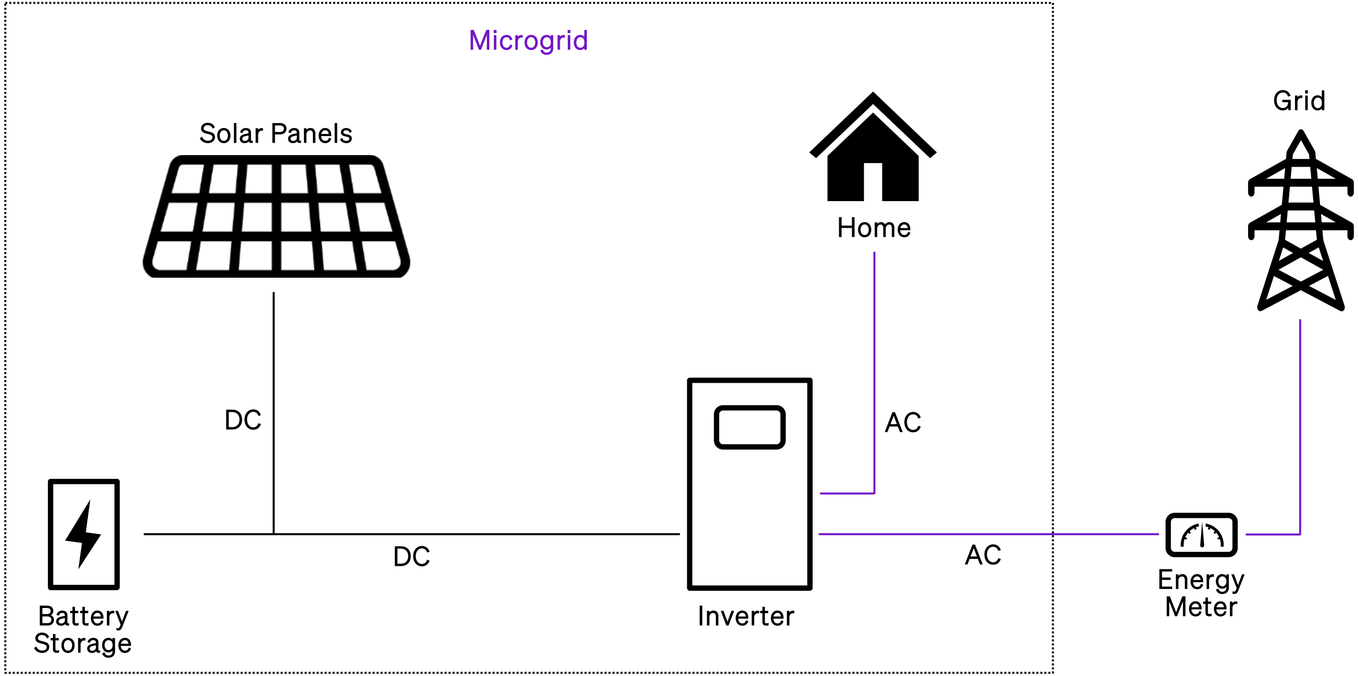
Continuous sources like nuclear and natural gas are essential for reliable electricity generation



Source: Department of Energy

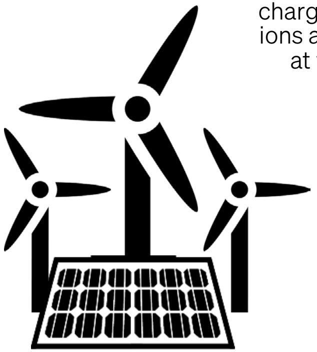
Solar 'Microgrids' Can Decentralize Power Generation Away From the Grid

Residential solar and storage systems can operate independently during outages and during periods of low demand



Hydrogen Can Be Used to Store Surplus Renewable Electricity Generation

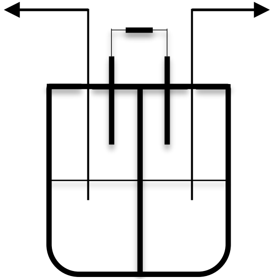
Surplus Renewable Electricity Generation



Powers Electrolysis

Oxygen is formed along with positively charged hydrogen ions and electrons at the anode

O2



Hydrogen ions and electrons recombine to form hydrogen gas at the cathode

Electrolysis splits water (H2O) into its constituents, Hydrogen (H2) and Oxygen (O2)

Creating Renewable Hydrogen Gas

H2 H2 H2 H2

Dive Deeper…

Further Reading & Watching

Reading:

- kW and kWh Explained – Solar Schools
- Levelized Cost of Energy – DOE
- U.S. Electricity Markets 101 – Resources for the Future
- Managing Oversupply – California ISO
- Solar Integration: Distributed Energy Resources and Microgrids – DoE

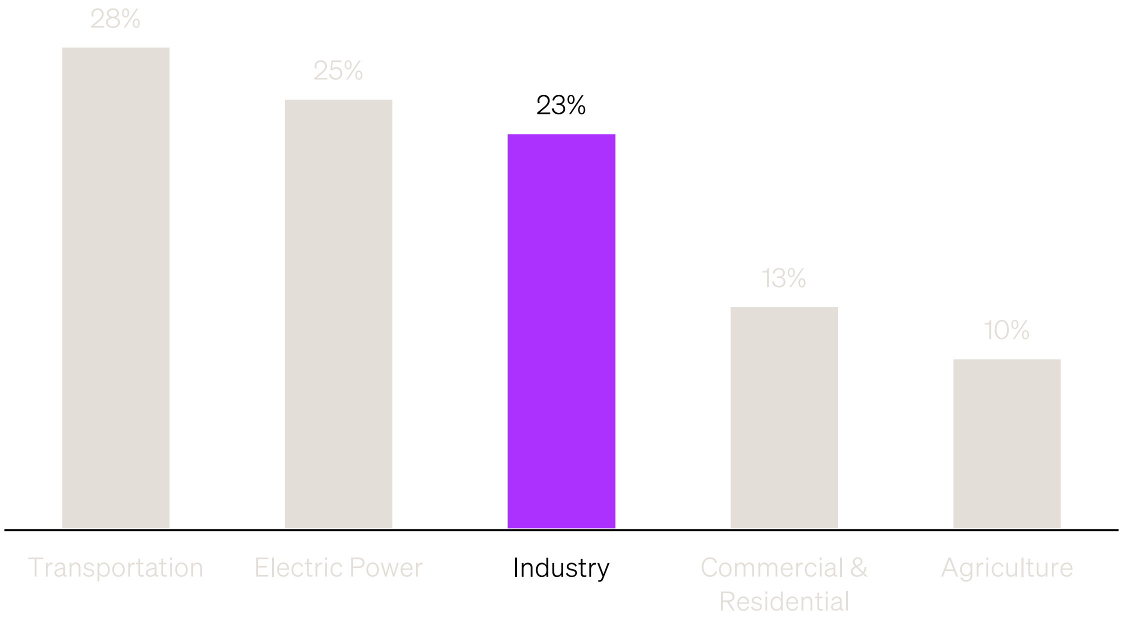
Watching:

- Creaky U.S. Power Grid Threatens Clean-Energy Progress – Reuters
- What is a Microgrid? – Western Power
- How Electrolysis Works – Penn State

CHAPTER 05

Decarbonizing industry

Industry is Responsible For 23% of U.S. Emissions

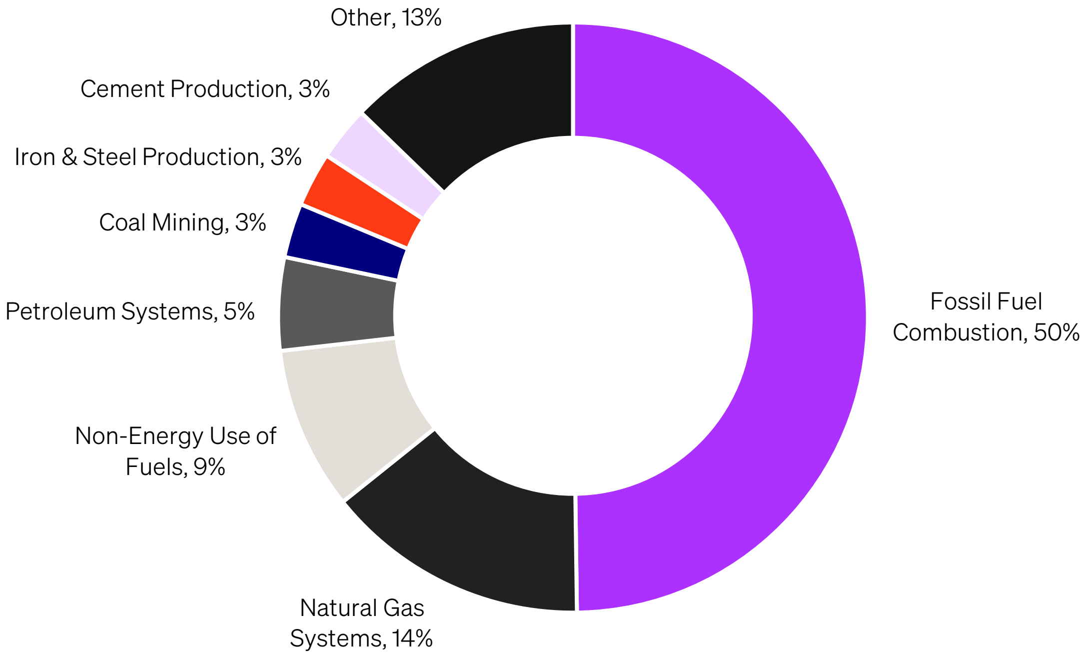


SOCIAL CAPITAL_

Source: EPA

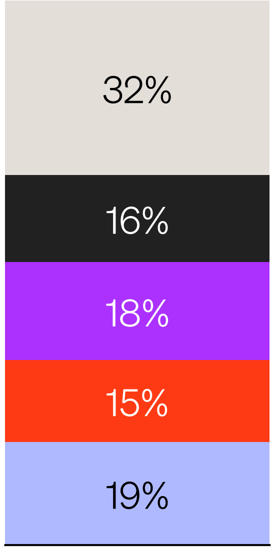
Industrial Sector Emissions Are Driven by Burning Fossil Fuels

U.S. Industrial Sector Direct GHG Emissions by Activity, 2021



Fossil Fuels Like Coal Are Burned to Generate Heat Across Key Industries

% Global Share of Estimated Fuel Consumption For Energy, 2017

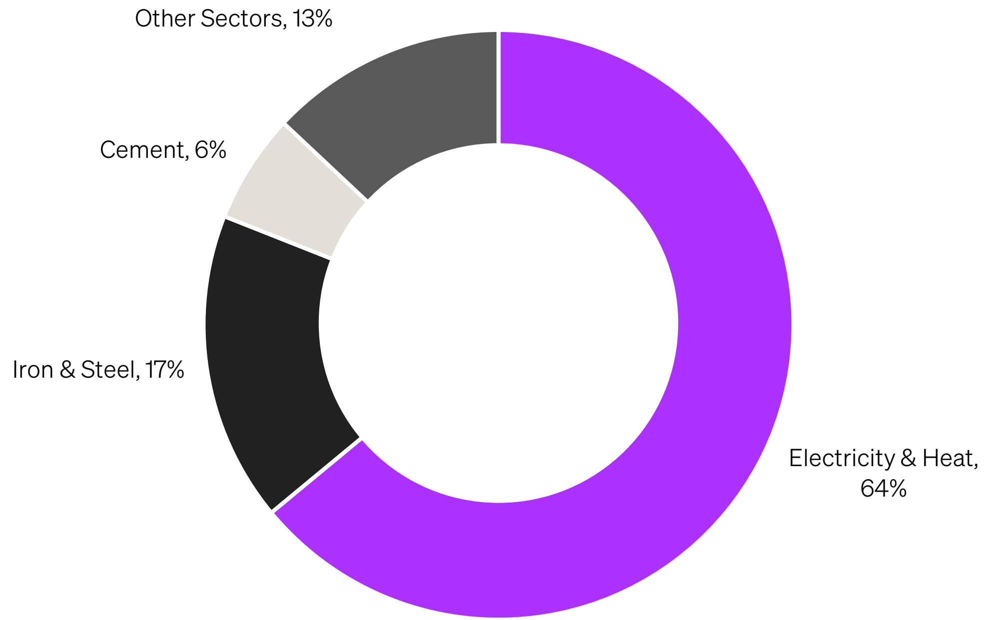


		Examples of processes
Very-high-temperature heat (>1,000°C)	32%	Melting in glass furnace, reheating of slab in hot strip mill, and calcination of limestone for cement production
High-temperature heat (400-1,000°C)	16%	Steam reforming and cracking in the petrochemical industry
Medium-temperature heat (100-400°C)	18%	Drying, evaporation, distillation, and activation
Low-temperature heat (≤100°C)	15%	Washing, rinsing and food preparation
Other (potential not assessed)	19%	

Source: McKinsey

Steelmaking and Cement Production Account For ~23% of Coal Demand

% Worldwide Coal Demand by Sector, 2020

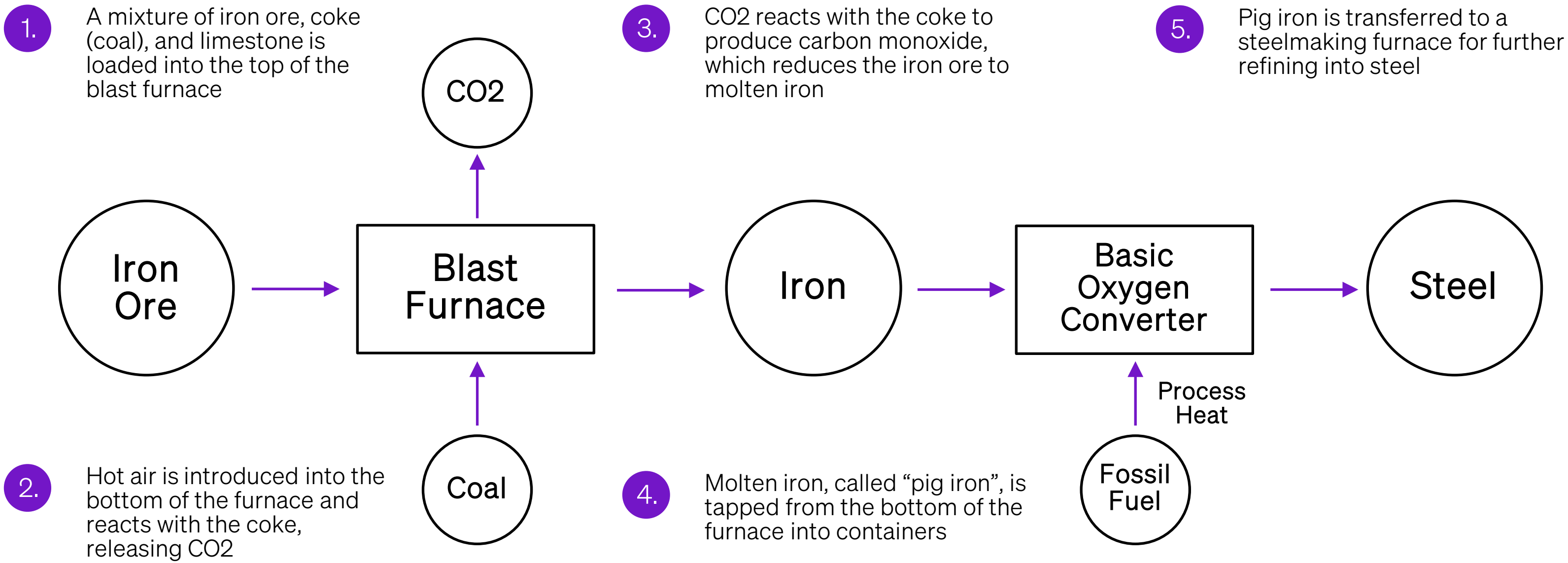


Source: IEA

How do we decarbonize steelmaking?

Traditional Steelmaking Emits Large Volumes of Greenhouse Gases

Blast Furnace Production Process



Source: International Iron Metallics Association, European Parliament

Hydrogen Can Replace Coal in Steelmaking

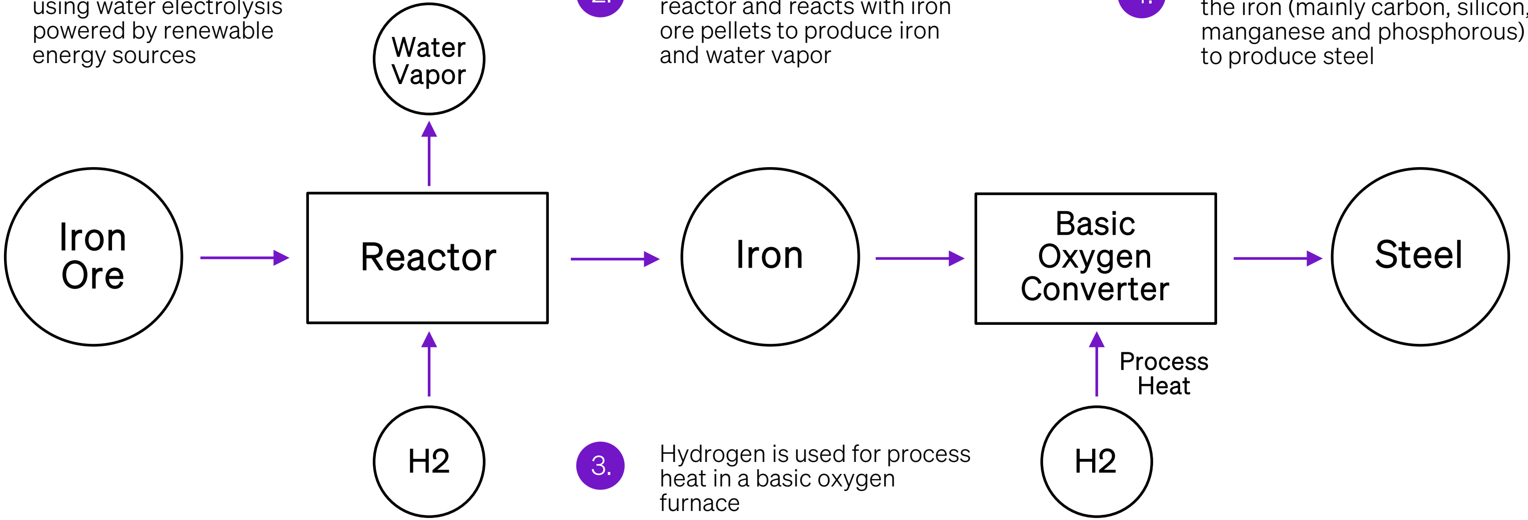
Hydrogen-Based Direct Reduction Process

1. Green hydrogen is produced using water electrolysis powered by renewable energy sources

2. Hydrogen gas is fed into the reactor and reacts with iron ore pellets to produce iron and water vapor

3. Hydrogen is used for process heat in a basic oxygen furnace

4. Oxygen reacts with impurities in the iron (mainly carbon, silicon, manganese and phosphorous) to produce steel



Source: International Iron Metallics Association, European Parliament

How do we decarbonize cement production?

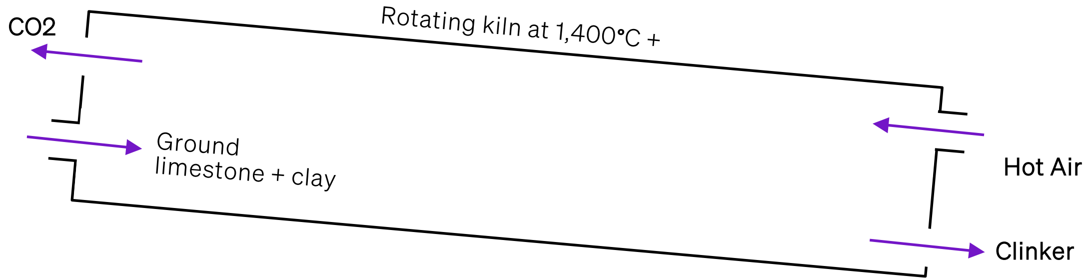
The Chemical Process of Cement Production is Highly Emissive

Cement is the key input in concrete, a vital global building material

1. Crushed limestone, clay, and other materials are fed into a huge cylindrical kiln and heated to 1,450°C using fossil fuels

2. The process of "calcination" breaks limestone into calcium oxide and CO_2

3. Other materials including clay, shale and iron ore are added to the calcinated limestone and produce "clinker", emerging as marble-sized grey balls



4. Clinker primarily consists of calcium silicates and residual free lime

5. Clinker is rapidly cooled to prevent further chemical reactions and is finely ground with gypsum to produce cement

6. Cement is mixed with water and aggregates as the binding agent to produce concrete, a key building material

Source: BBC

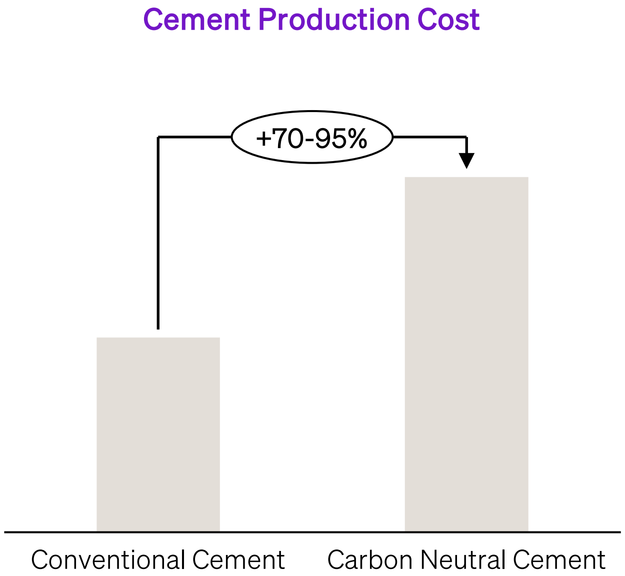
Capturing and Using Carbon Can Produce Carbon Neutral Concrete

Carbon capture can be deployed across a wide range of industries

Use Sustainable Fuel	Capture Flue Gases	Inject CO_2 into Concrete Mix	Mineralize CO_2 to Produce Aggregate
▪ Replace coal and natural gas with renewable-powered electric kilns or clean hydrogen	▪ Capture CO_2 emitted from cement plants ▪ Pre-treat captured gases to remove impurities and water vapor ▪ Compress and transport the CO_2	▪ Inject CO_2 into fresh concrete during mixing ▪ CO_2 will react with water in the concrete mix to form calcium carbonate ▪ This improves the compressive strength of concrete and reduces the amount of cement required	▪ CO_2 is mixed with selected feedstock materials (such as steel slag and fly ash) in a reactor to produce stable carbonate compounds ▪ The resulting carbonates are processed to form aggregates suitable for use in concrete

Source: CarbonCure, Blue Planet Systems

But Carbon Neutral Methods of Producing Steel and Cement Are More Expensive Than Legacy Methods



SOCIAL CAPITAL_

Source: Bellona, Rocky Mountain Institute

Dive Deeper…

Further Reading & Watching

Reading:

- The Potential of Hydrogen For Decarbonising Steel Production – European Parliament
- Portland Cement Manufacturing – EPA
- Permanent Carbon Capture – Blue Planet Systems

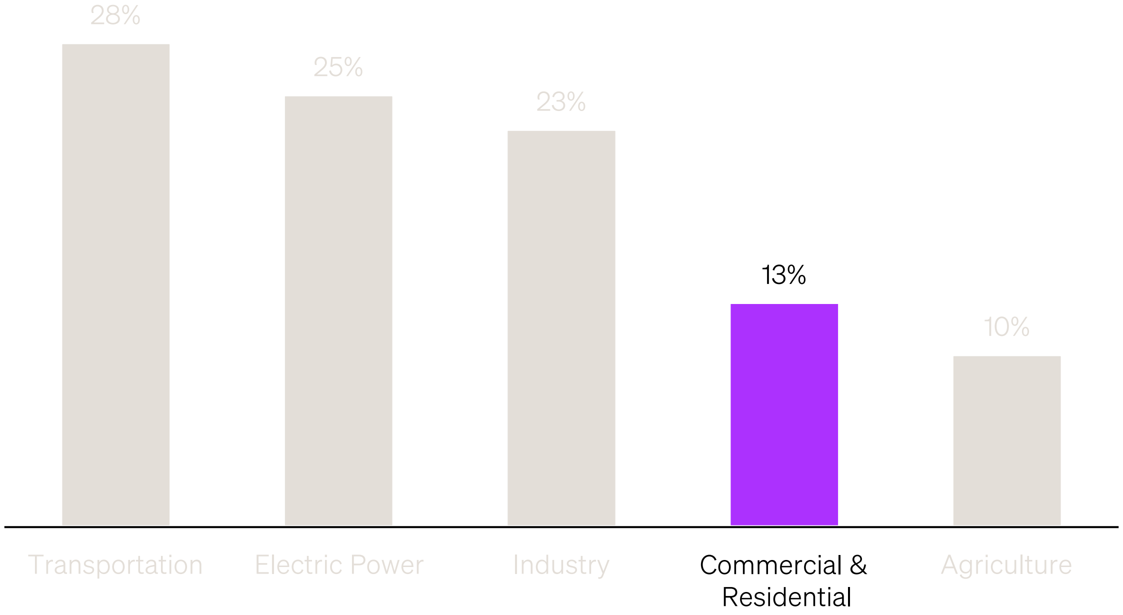
Watching:

- Steel Manufacturing – Matallurgy Data
- How Cement is Made – Portland Cement Association
- CarbonCure's Concrete Technology – CarbonCure

CHAPTER 06

Decarbonizing commercial & residential emissions

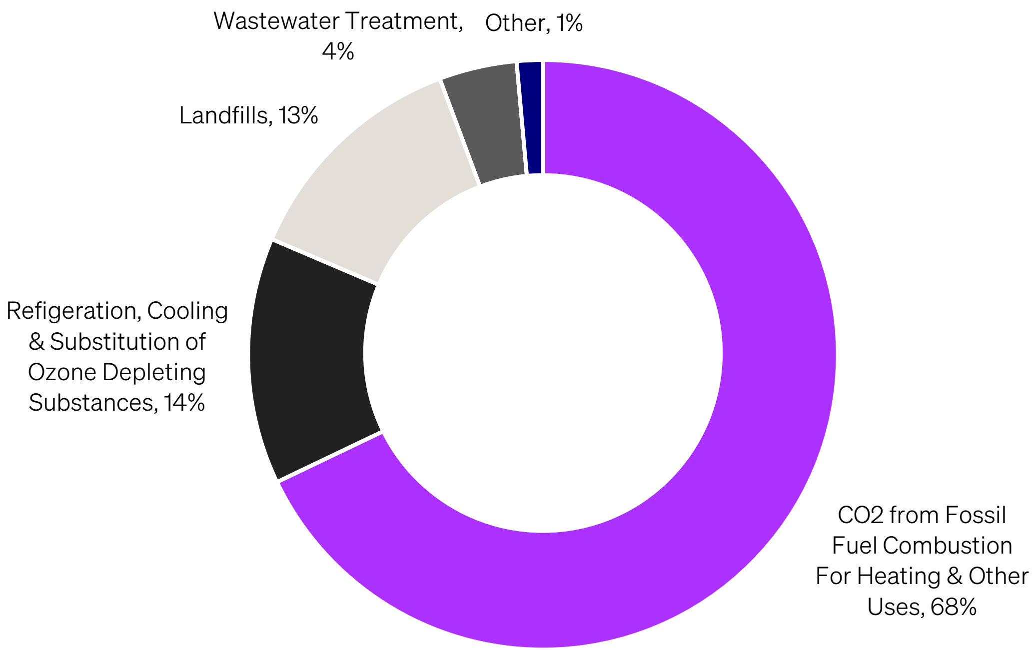
Commercial and Residential Sectors Are Responsible For 13% of Total U.S. Emissions



Source: EPA

Heating and Cooling Drive Commercial & Residential Sector Emissions

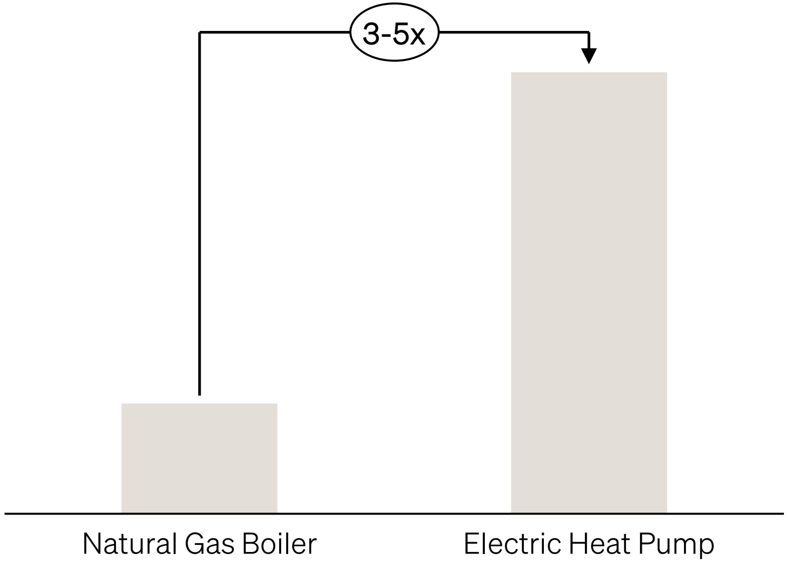
U.S. Commercial & Residential Sector Direct GHG Emissions by Activity, 2021



Source: EPA

Electric Heat Pumps Are More Efficient Than Gas Furnaces, and Can Replace Fossil Fuels For Both Heating and Cooling

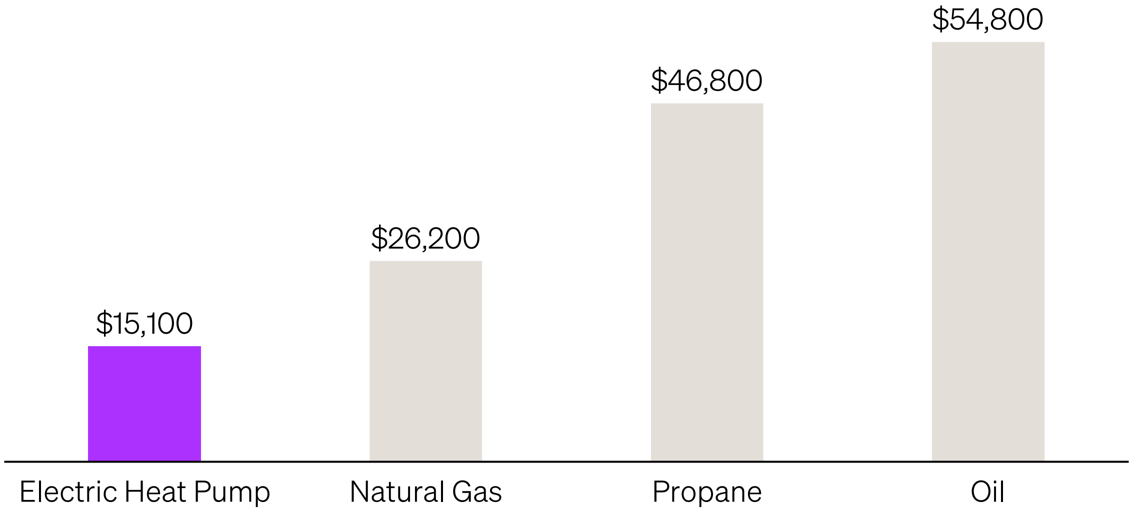
Energy Efficiency



Source: EPA

The Lifetime Cost of Electric Heat Pumps is Significantly Lower Than Burning Fossil Fuels

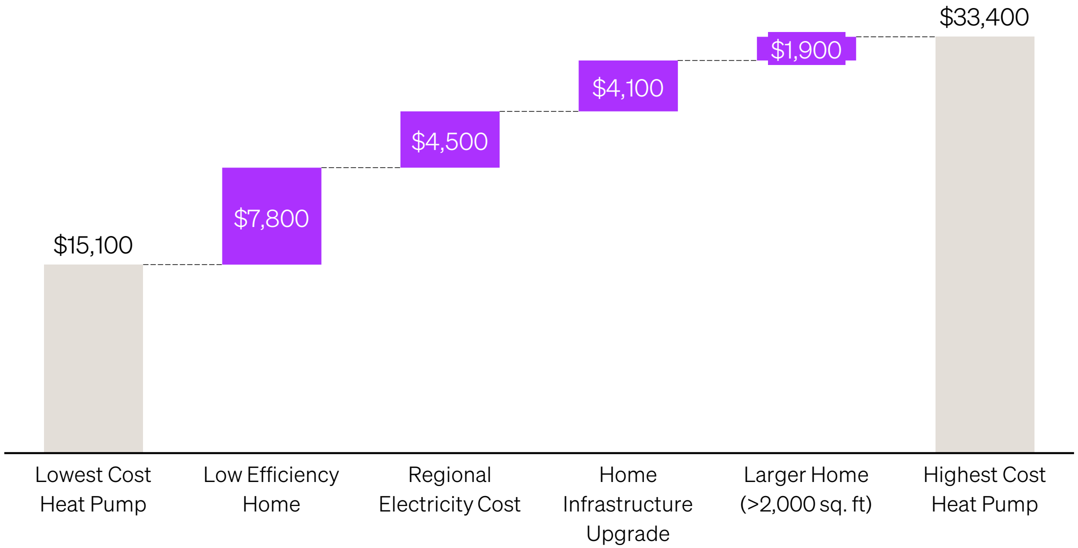
Total Cost of Ownership Excluding State Incentives



Source: Harvard Business School

But Regional Factors and Infrastructure Upgrade Requirements Can Make the Installation and Lifetime Cost of Heat Pumps Much Higher

Total Cost of Ownership Waterfall (Lowest to Highest)



Source: Harvard Business School

Dive Deeper…

Further Reading & Watching

Reading:

- Why Are We Still Using Super-Greenhouse Gases in our Home Air Conditioners? – TechCrunch
- How Do Heat Pumps Work? – National Grid
- Everything You Need to Know About the Wild World of Heat Pumps – MIT Technology Review
- The Rise of Electric Heat Pumps – Harvard

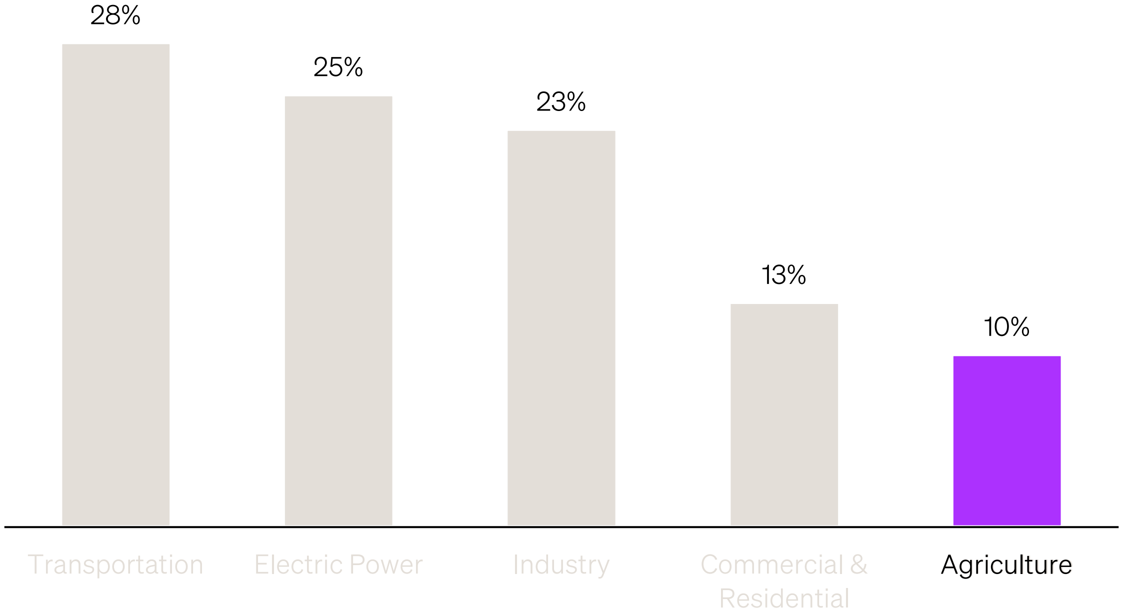
Watching:

- Heat Pumps Explained – The Engineering Mindset
- The Cruel Irony of Air Conditioning – MinuteEarth

CHAPTER 07

Decarbonizing agriculture

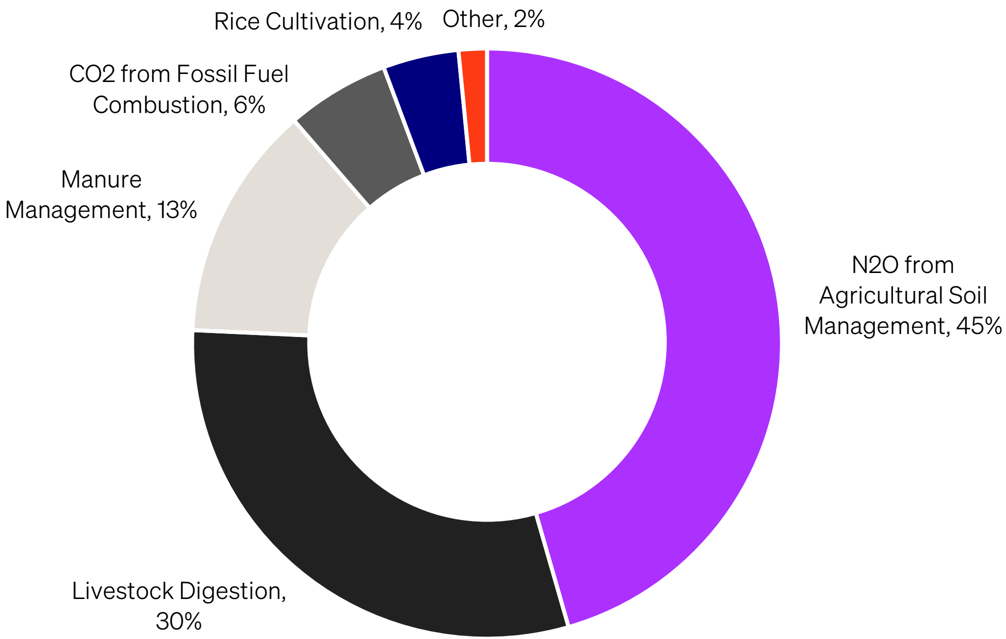
Agriculture is Responsible For 10% of U.S. Emissions



Source: EPA

Soil Management and Livestock Drive Agriculture Emissions

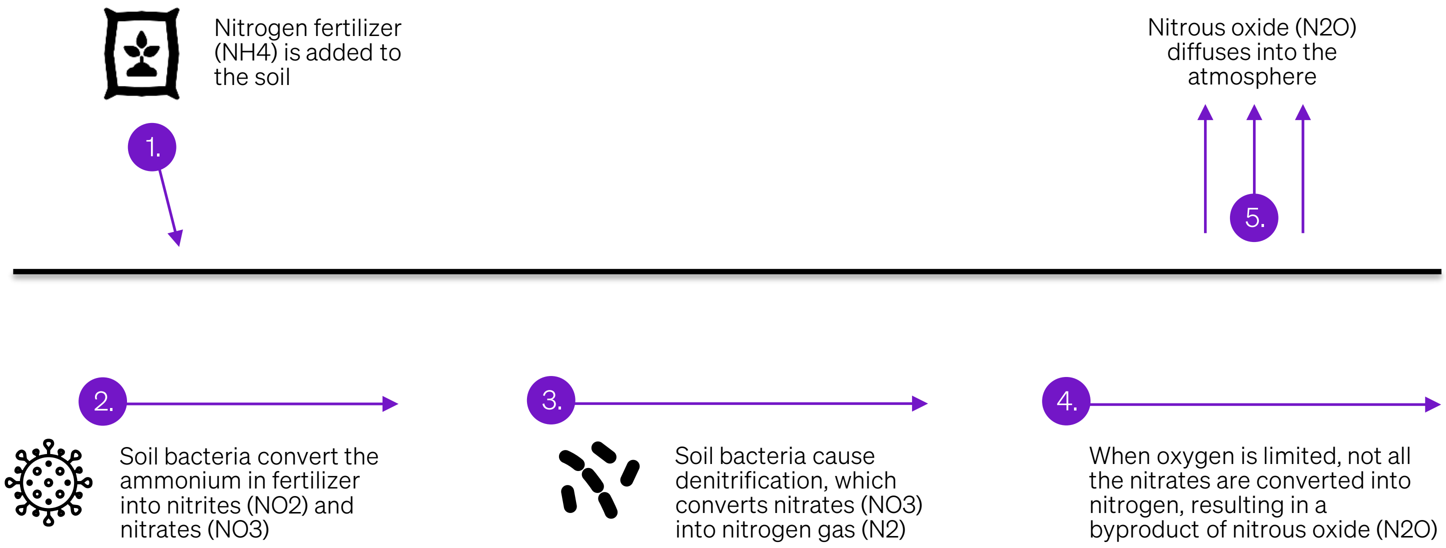
U.S. Agriculture Sector Direct GHG Emissions by Activity, 2021



Source: EPA

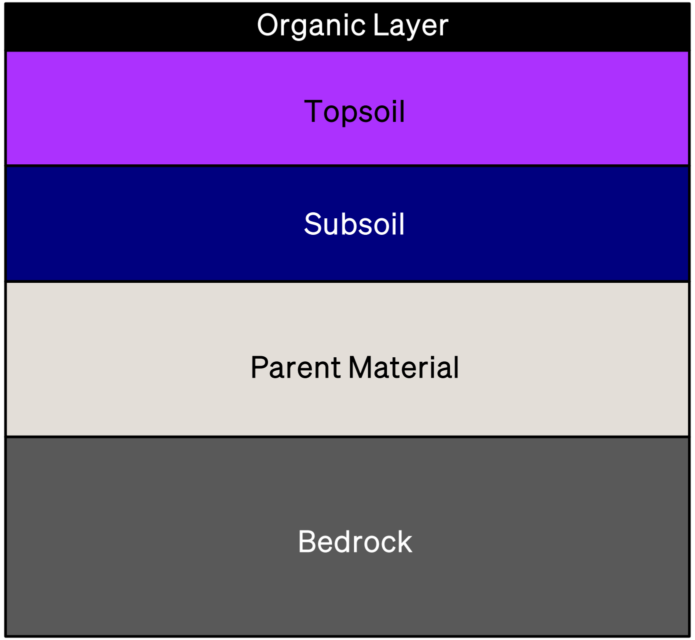
How do we decarbonize soil management?

Applying Fertilizer to Grow Crops Results in Nitrous Oxide Emissions



And Tilling Soil Accelerates Decomposition of Organic Matter Which Releases CO_2

Soil stores carbon in various organic and inorganic forms, including living plant roots and decomposed organic matter



1. Physical and chemical weathering of parent rock material breaks rocks down into smaller particles including sand, silt and clay
2. Plants and animals decompose and contribute organic matter to the surface, which becomes part of the developing soil
3. Microorganisms including bacteria and fungi help to decompose dead plant and animal material to bring organic matter into the soil
4. Over time, organic matter decomposes into stable compounds called “humus”, a dark, carbon-rich soil which forms the top organic layer
5. When soil is tilled, it exposes previously buried organic matter, leaving it open to microbial decomposition which releases CO_2

Source: Civilspedia, Queensland Government

Reduced Tillage and Cover Crops Can Reduce GHG Emissions From Soil Management

Reduced tillage and cover crops can help to maintain the integrity of soil and carbon stored within

Reduced Tillage	Cover Crops
▪ Reduced tillage minimizes organic matter breakdown, reducing N2O emissions and storing more carbon in the soil ▪ Reduced tillage also leaves crop residues on the surface of soil, which can maintain and increase levels of soil organic carbon	▪ Cover crops like legumes naturally add nitrogen to soil and improve nutrient cycling, reducing the need for synthetic fertilizers ▪ Cover crops sequester carbon from the atmosphere and eventually become a source of stable organic carbon in the soil ▪ Cover crops protect soil from erosion, which helps to maintain soil structure

Source: UC Agriculture & Natural Resources, EESI, Western Australia Department of Agriculture and Food

How do we decarbonize livestock?

Livestock Emit Methane Through Excretion of Gases Produced During Digestion

Cow Digestive System

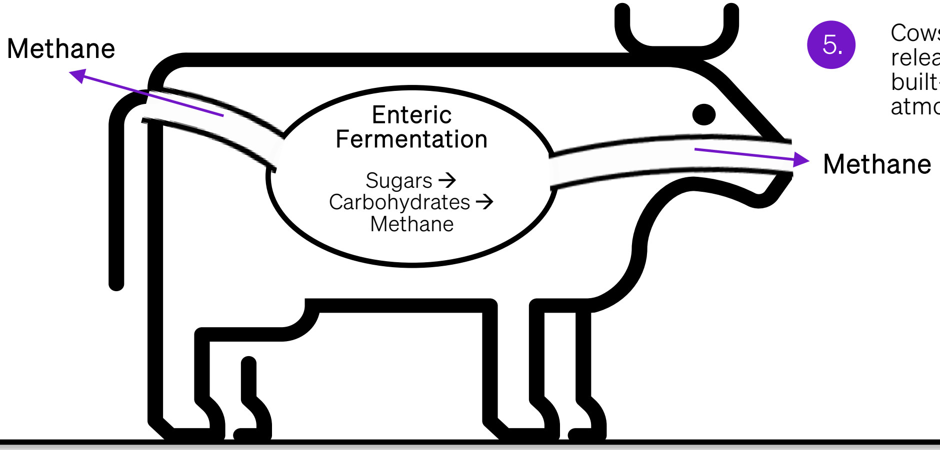
1. Cow consumes plant-based feed such as grass, hay or grains

2. Plant material enters a section of the cow's stomach called the "rumen"

3. Microbes in the rumen break down complex carbs into simpler compounds through fermentation

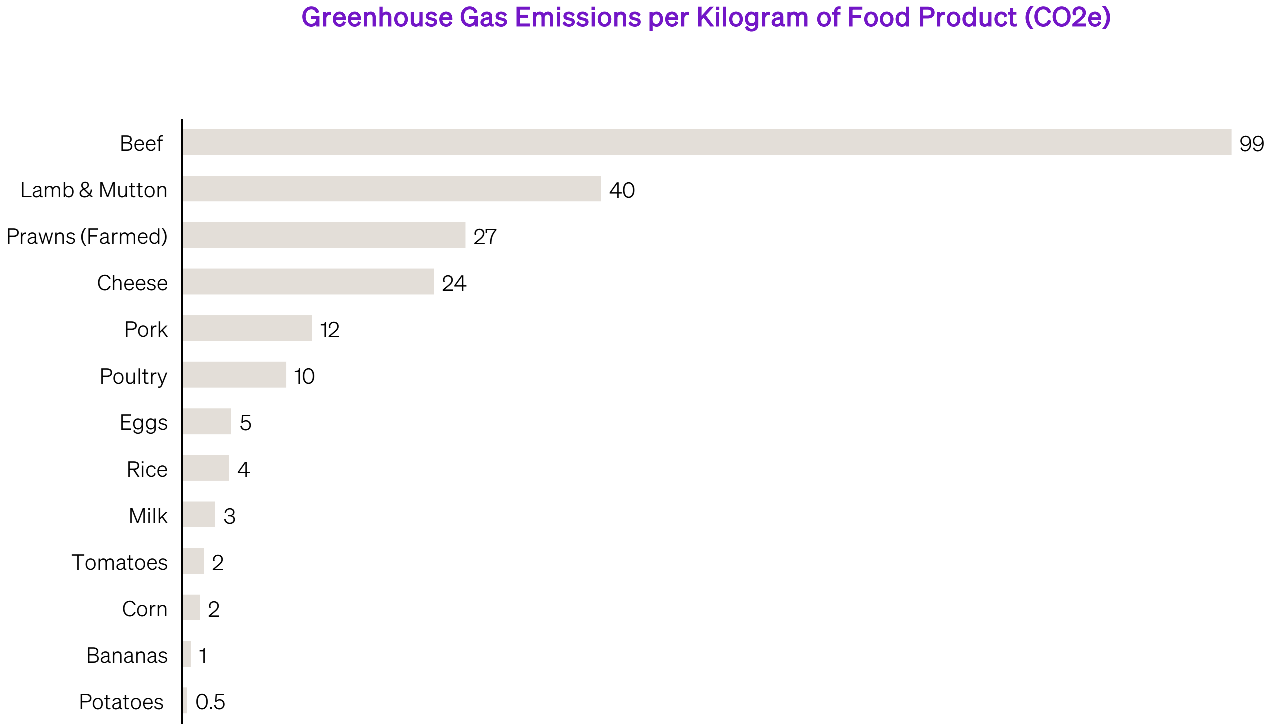
4. Hydrogen gas accumulates during fermentation and reacts with carbon dioxide to produce methane

5. Cows periodically belch to release methane and other built-up gases into the atmosphere



Source: Our World in Data

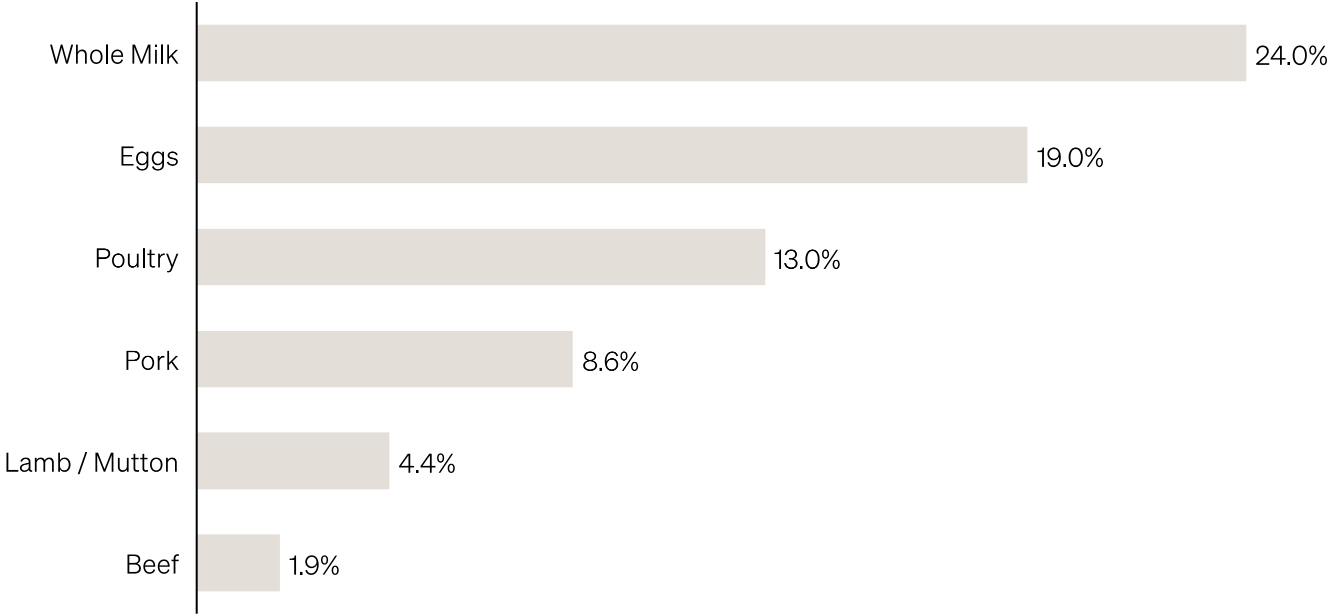
Beef Production Emits More Greenhouse Gases Than Any Other Food Product



Source: Our World in Data

And Beef Production is Less Calorie Efficient Than Other Proteins

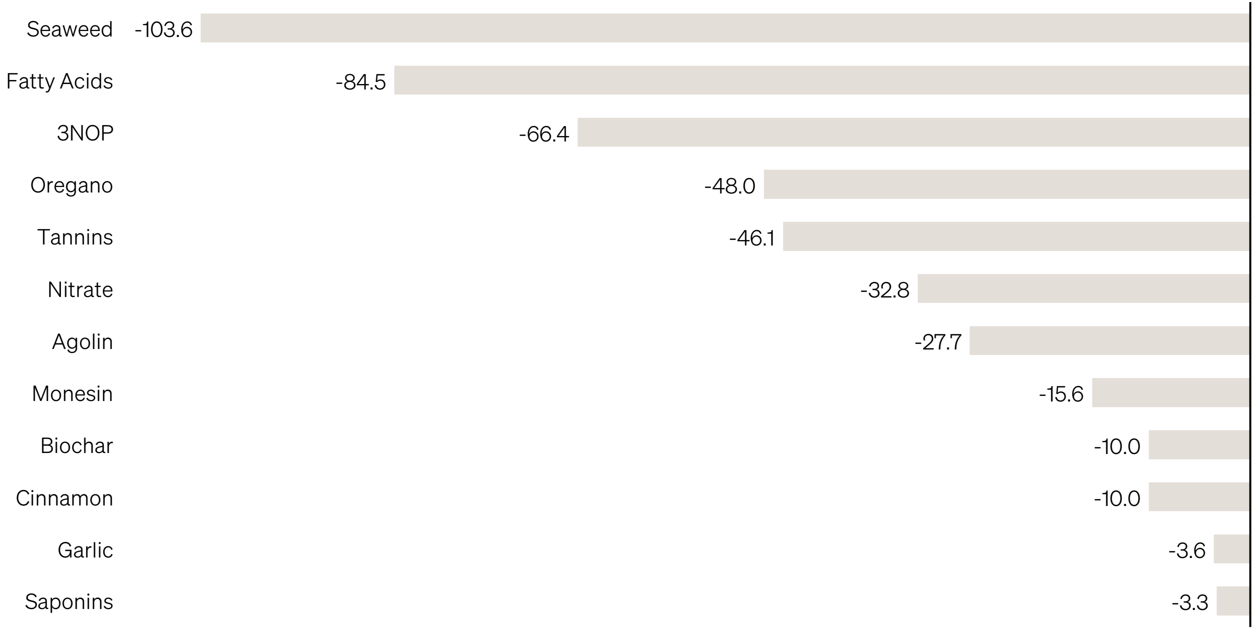
Percentage of Caloric Inputs as Feed Effectively Converted to Animal Product



Source: Our World in Data

Cattle Feed Additives Can Reduce Methane Emissions From Cows

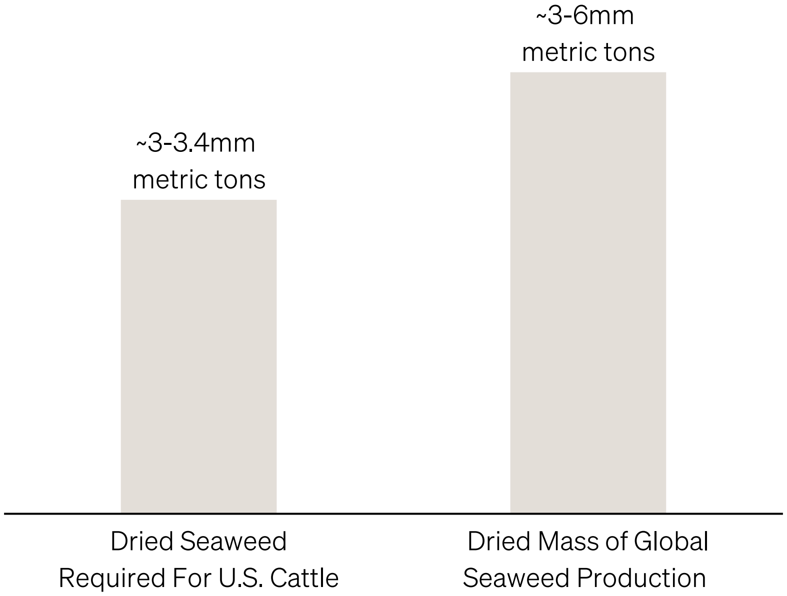
Mean Methane Reductions From Feed Additives (grams/day)



Source: UC Davis

But Harvesting Enough Seaweed For the World's ~1.4Bn Cows is Difficult to Scale

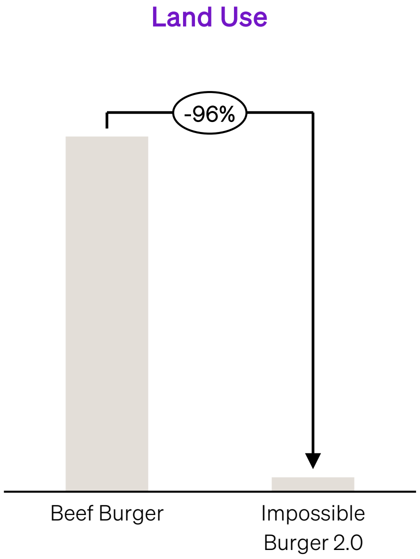
Seaweed additives for U.S. cows alone would consume over half of global seaweed production

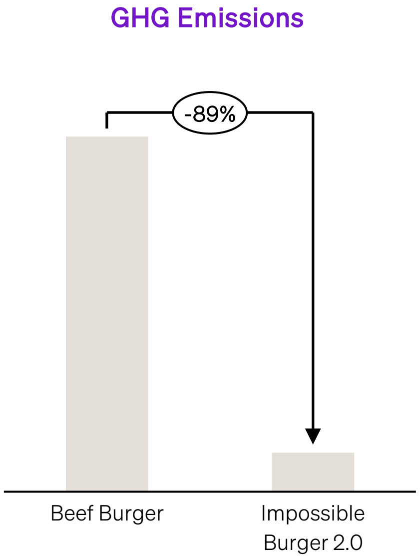


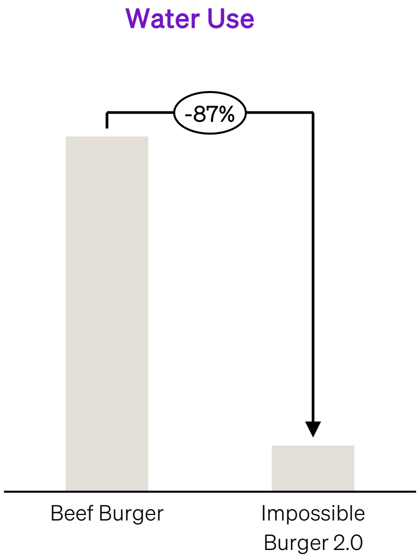
Source: Frontiers in Veterinary Science

Plant-Based Meat Offers a More Environmentally Friendly Alternative to Beef

Impossible Burger 2.0 vs Conventional Meat







Source: Good Food Institute

But Existing Plant-Based Meat Options Use Large Ingredient Lists Which May Carry Potential Health Risks

	Ground Beef (20% fat)	Beyond Burger	Impossible Burger
Calories	270	290	240
Saturated Fat	6.7g	5.0g	8.0g
Protein	6.7g	5.0g	8.0g
Sodium	75mg	450mg	370mg
Ingredients	Beef	Water, pea protein (16%), canola oil, coconut oil, rice protein, flavoring, stabilizer (methylcellulose), potato starch, apple extract, color (beetroot red), maltodextrin, pomegranate extract, salt, potassium salt, concentrated lemon juice, maize vinegar, carrot powder, emulsifier (sunflower lecithin)	Water, plant protein (21%) (soy), sunflower oil, coconut oil, thickener (INS 461), glutamic acid, natural flavors, cultured dextrose, modified starch, yeast extract, soy leghemoglobin (genetically modified), salt, antioxidant (INS 307b), vitamins and minerals (zinc gluconate, niacin (Vitamin B3), thiamine hydrochloride (Vitamin B1), pyridoxine hydrochloride (Vitamin B6), riboflavin (Vitamin B2), Vitamin B12).

Dive Deeper…

Further Reading & Watching

Reading:

- How Soils Form – Queensland Government
- No-Till Farming Improves Soil Health and Mitigates Climate Change – Environmental and Energy Study Institute
- Plant-Based Meat for a Growing World – Good Food Institute
- Impossible and Beyond: How Healthy Are These Meatless Burgers? – Harvard Health

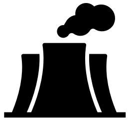
Watching:

- Carbon Farming: A Climate Solution Under Our Feet – NHK World Japan
- Cow Burps Are a Climate Problem. Can Seaweed Help? – Vox

CHAPTER 08

Offsetting other emissions

Many Companies Have Prioritized Offsetting Their Direct and Indirect Emissions to Reach Net Zero

Scope 1 Direct Emissions	Scope 2 Indirect Emissions	Scope 3 Indirect Emissions
Direct emissions from sources that a company owns and controls	Indirect emissions from how the energy a company uses is produced	Indirect emissions from the rest of a company’s value chain
E.g. Direct CO2 emissions from a company’s vehicle fleet	E.g. Indirect emissions from using fossil-fuel produced electricity	E.g. Indirect emissions generated by suppliers of input products
		

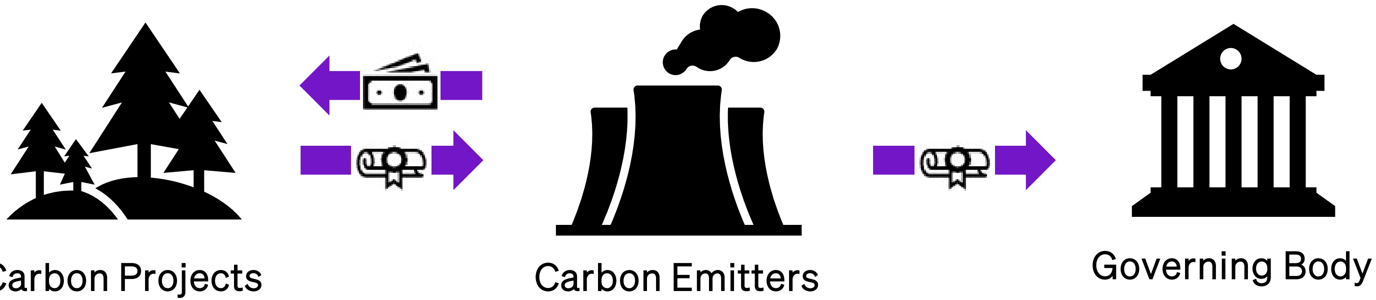
Source: National Grid

Carbon Projects Generate Credits For Companies to Purchase and Offset Their Emissions

Projects that reduce or remove carbon emissions from the atmosphere generate carbon offsets

Companies with carbon footprints purchase offsets to comply with internal or external targets

Emitters receive these credits and retire them with verified governing bodies to meet their goals



Source: Climate Resources

Technology-Based Carbon Projects Are Considered More Permanent Than Nature-Based Solutions

Lowest permanence → Highest permanence

Nature-Based Projects			Technology-Based Projects
▪ Landfill methane capture ▪ Methane avoidance at farms ▪ Improved cookstoves	▪ Improved forest management ▪ Avoided deforestation ▪ Wetland restoration	▪ Reforestation ▪ Regenerative agriculture ▪ Biochar	▪ Direct air capture ▪ Carbon capture & storage ▪ Carbon mineralization

Source: 3Degrees, Reuters

But Technology-Based Projects Are Much More Expensive Than Nature-Based, Which Makes Them Harder to Scale

Source: Abatable

Dive Deeper…

Further Reading & Watching

Reading:

- What Are Scope 1, 2 and 3 Carbon Emissions? – National Grid
- Long-Term Carbon Offsets Outlook 2023 – Bloomberg
- Carbon Credits Prices in the Voluntary Carbon Market – Abatable

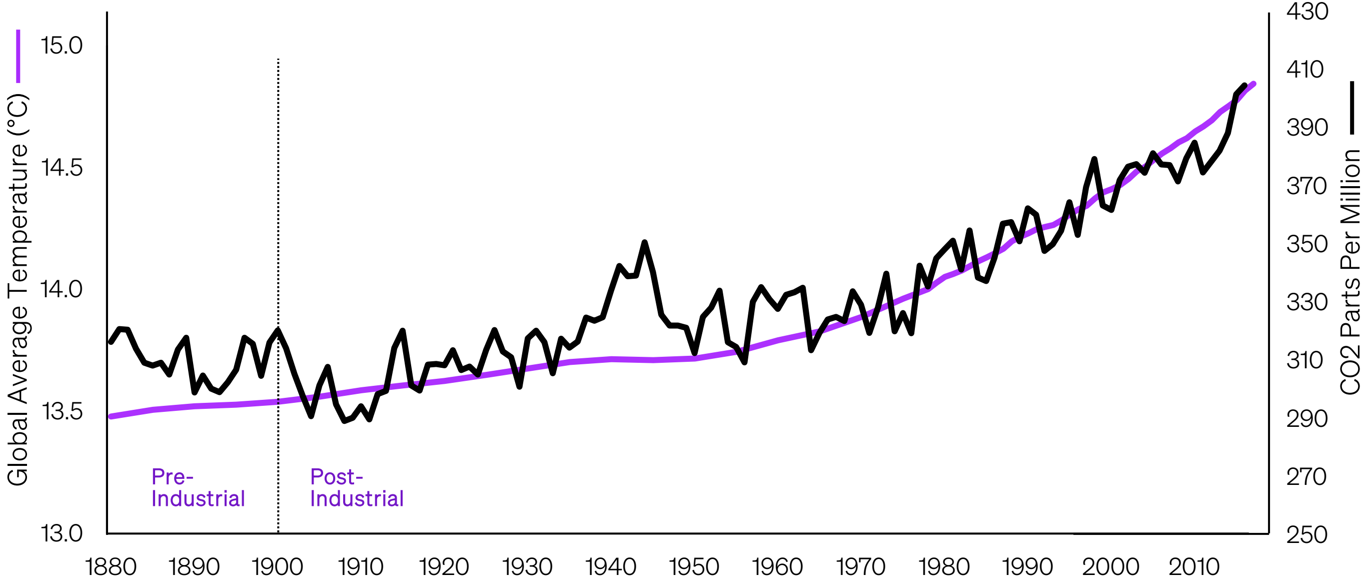
Watching:

- Scope 1, 2, and 3 Emissions Explained – Climate Now
- Carbon Credits Explained – South Pole
- The Carbon Offset Problem – Wendover Productions

CHAPTER 09

Wrapping up...

Rising Atmospheric Greenhouse Gas Concentrations and Global Temperatures Presents a Risk of Dangerous Warming



Reaching Net Zero GHG Emissions Will Require an Energy Transition Across Every Major Sector

Sector	Source of Emissions	Solution
Transportation	Fossil Fuels	Electrification, Hydrogen, Sustainable Fuels
Electric Power	Fossil Fuels	Renewables & Nuclear
Industry	Fossil Fuels	Electrification, Hydrogen & Carbon Capture
Commercial & Residential	Fossil Fuels	Electrification
Agriculture	Soil Management & Livestock	Sustainable Agriculture & Dietary Change

Source: UCAR

Future Deep Dives

Month	Theme	Deep-Dive	Summary
Dec	**Energy Transition**	**The Global Energy Transition**	**What is climate change and why is it happening? Where are global carbon emissions coming from? What are the key pieces of legislation we have implemented to solve this?**
Jan	Deep Tech	A Primer on Artificial Intelligence	What is Artificial Intelligence and what are the different types? How do the various models work? How is value created? What are the risks?
Feb	Life Sciences	The Business Model of Healthcare	What are the incentives that drive the behavior and outcomes of drug companies, insurers and hospitals? What new disruptions are at hand?
Mar	Economic Analysis	'Go Woke, Go Broke'?	Which companies have 'gone woke' and why? Where has this business strategy succeeded and failed? Do companies that 'go woke' underperform their peers?
Apr	Energy Transition	Residential Solar and the Future of Energy	Outline of the solar value chain, industry trends, and how residential solar could disrupt traditional utilities.
May	Deep Tech	The Future of Space	What are the legacy and emerging business models built around space? How do we get to space today? What will space look like tomorrow?
Jun	Life Sciences	The Economics of Drug Development	How do the economics of drug companies work? Why have biotech sector returns been so poor over the past decade?
Jul	Socio-Political Trends	Is India the Next Economic Giant?	Where is India's economy today and where might it be tomorrow? What are the key demographic and social factors that are driving the country's development?
Aug	Energy Transition	Replacing Animal Meats	What are global trends driving protein demand? Do we need plant-based meat? What are the challenges to production and adoption?
Sep	Deep Tech	Moore's Law and Next Steps for Silicon	What is Moore's Law and has it broken down? What are the different types of semiconductors? Why are companies moving towards more custom-designed silicon?
Oct	Economic Analysis	When Companies Go 'Ex-Growth'	What does it mean for a company to go 'ex-growth'? Why does it happen? What are the implications for valuation? How can companies respond?
Nov	Socio-Political Trends	A Demographic and Social Breakdown of America	Where is America today? A visual representation of our democracy, demography, economy, quality of life, progress and more.

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