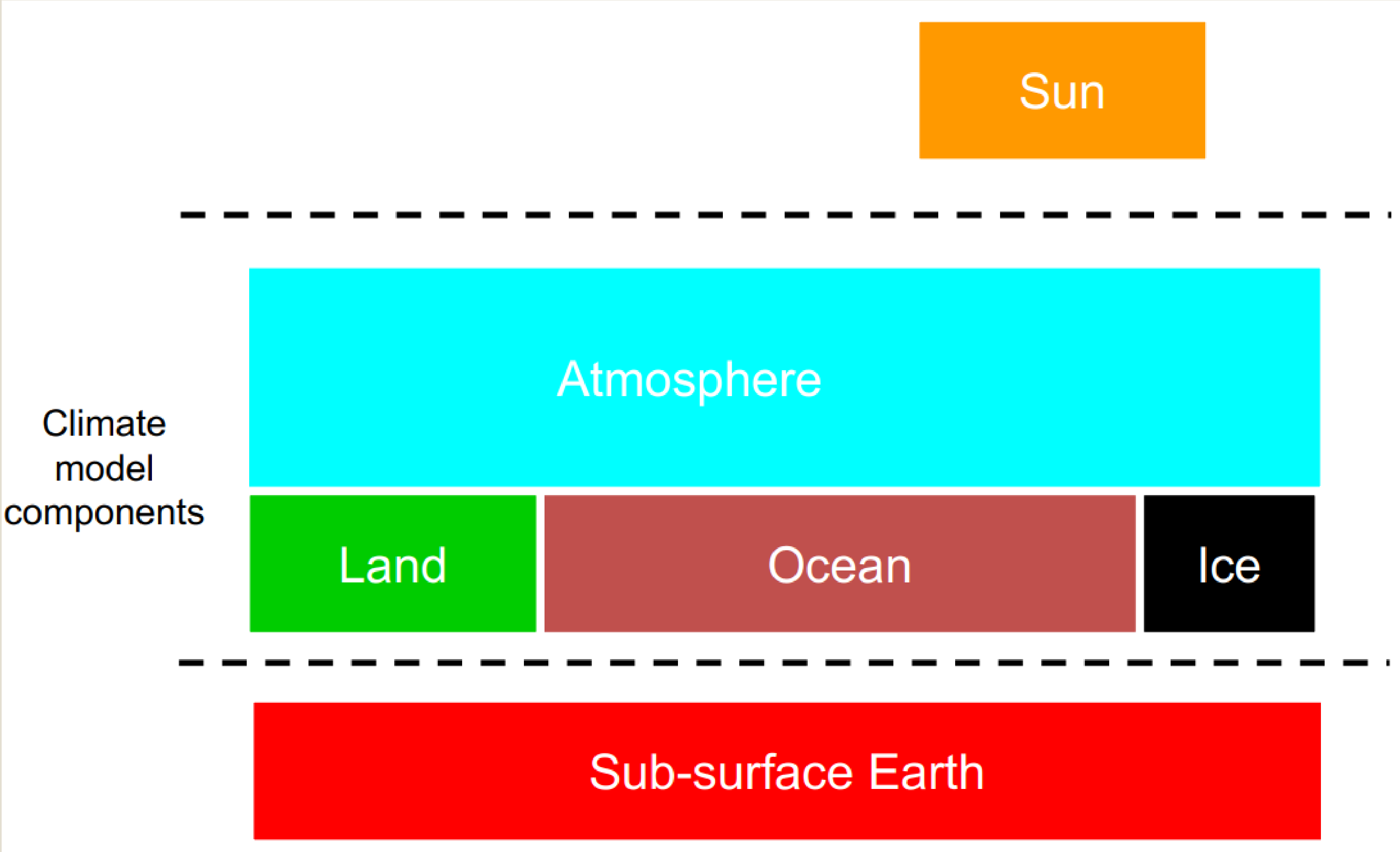
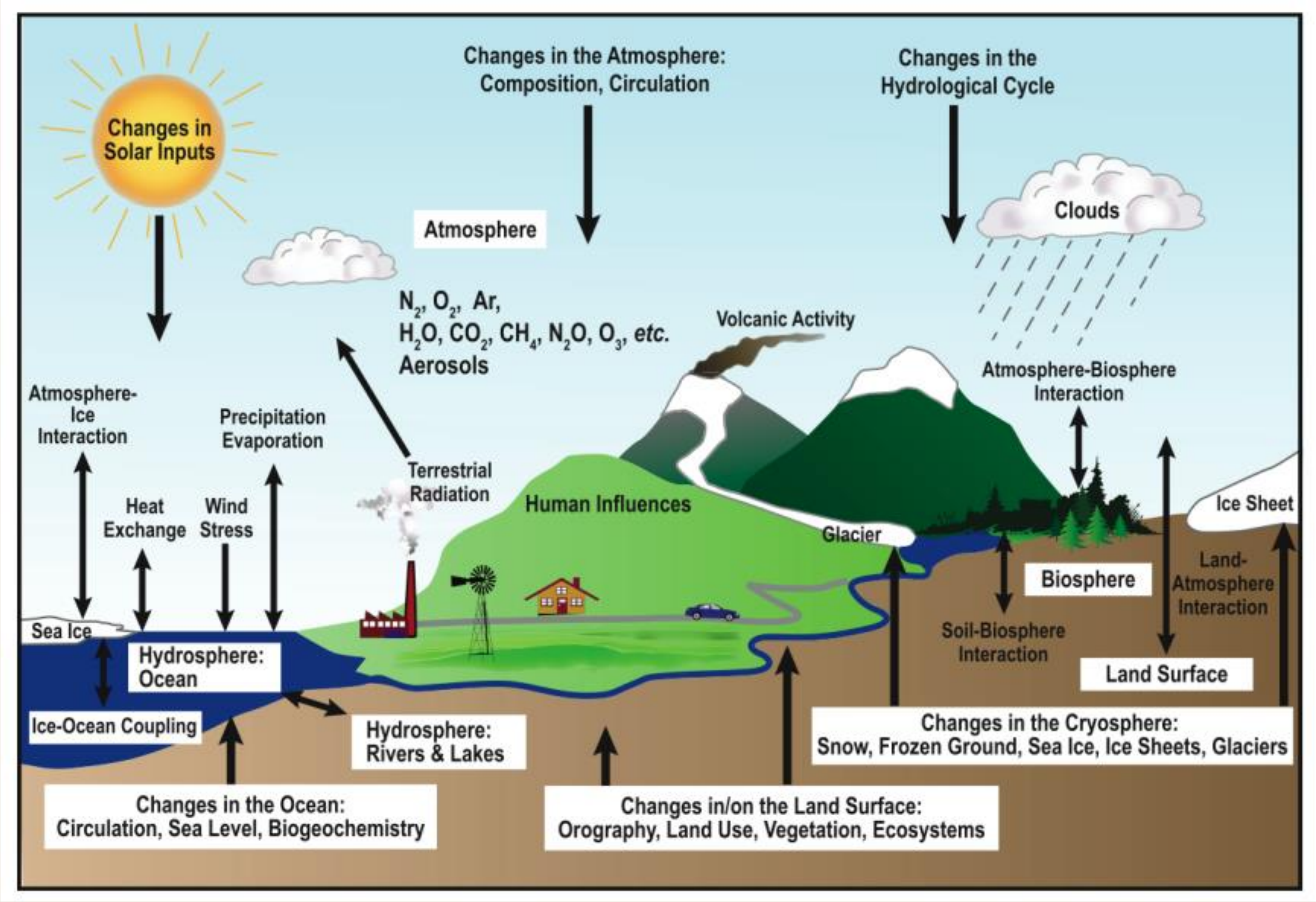
GLOBAL CLIMATE CHANGE & MITIGATION

Sheila Tobing

Earth's Climate System



Factors Driving Climate



Carbon Cycle

- **Carbon Stocks / Reservoirs**:
    - Land surface layers: 2,190 GT
    - Ocean surface: 1,020 GT
    - Intermediate and deep ocean: 38,100 GT
    - Atmosphere: 750 GT
- **Carbon Flows**:
    - Fossil fuel combustion and cement production release 5.5 GT/yr into the atmosphere.
    - 2 GT/yr dissolves into ocean surfaces.
    - Land use changes add 1.1 GT/yr to the atmosphere.
    - Net vegetation production and respiration remove 1.4 GT/yr from the atmosphere.

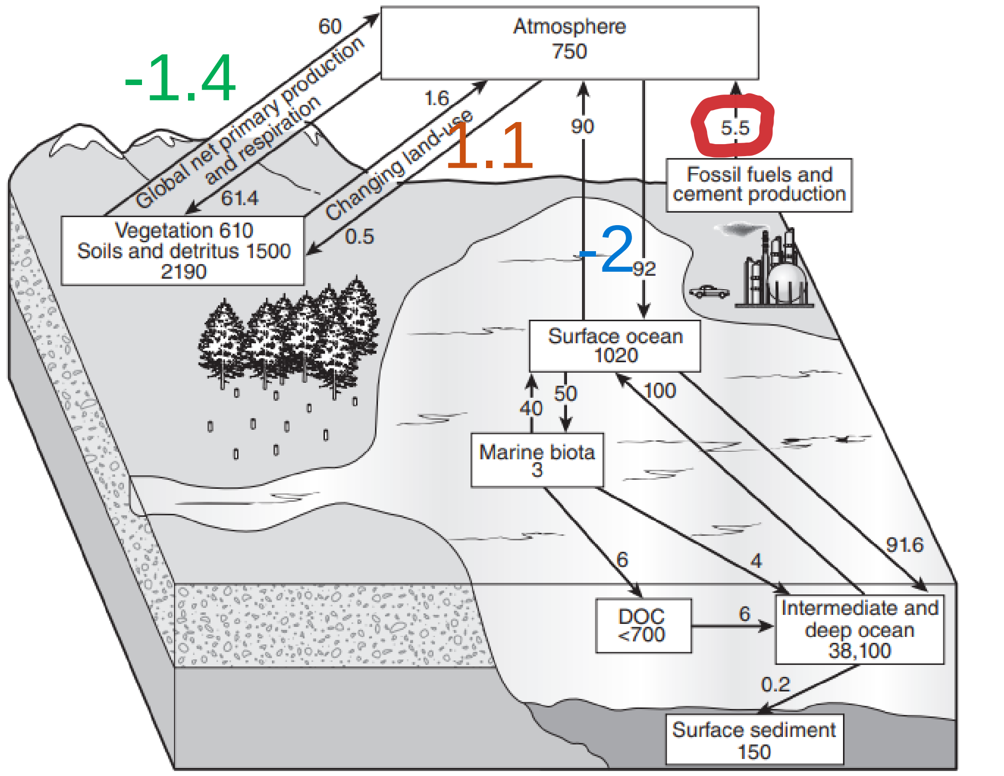


Figure 7.4
The global carbon cycle. This diagram provides a particularly good perspective of all the processes that affect the cycling of carbon in the earth's biosphere. Carbon reservoirs (where carbon is stored) are represented by boxes, and the numbers in the boxes indicate the gigatonnes of carbon contained in each reservoir. Carbon fluxes (transfers of carbon between reservoirs) are represented by arrows; their units are given in gigatonnes of carbon per year. A gigatonne is the same quantity as a petagram, which is 10^{15} grams. Source: Schimel et al. (1995), figure 4.

Carbon Cycle

- **Biomass Planting**:
  - Offsetting fossil-fuel emissions with biomass requires understanding carbon sequestration in vegetation, soils, and CO_2 transfers with the atmosphere.
  - Geologic carbon sequestration is effective if storage integrity is maintained.
- **Energy and Emissions**:
  - Additional energy is needed for planting or sequestration, leading to more emissions.
  - Carbon capture and storage (CCS) technologies capture about 90% of emissions, but increased energy use still raises emissions.
- **Carbon Cycle Dynamics**:
  - Marine biota in oceans hold about 3 GT of carbon, a small but dynamic reservoir.
  - Changes in marine biota activity can significantly impact carbon fluxes in the ocean and atmosphere.

Carbon Cycle

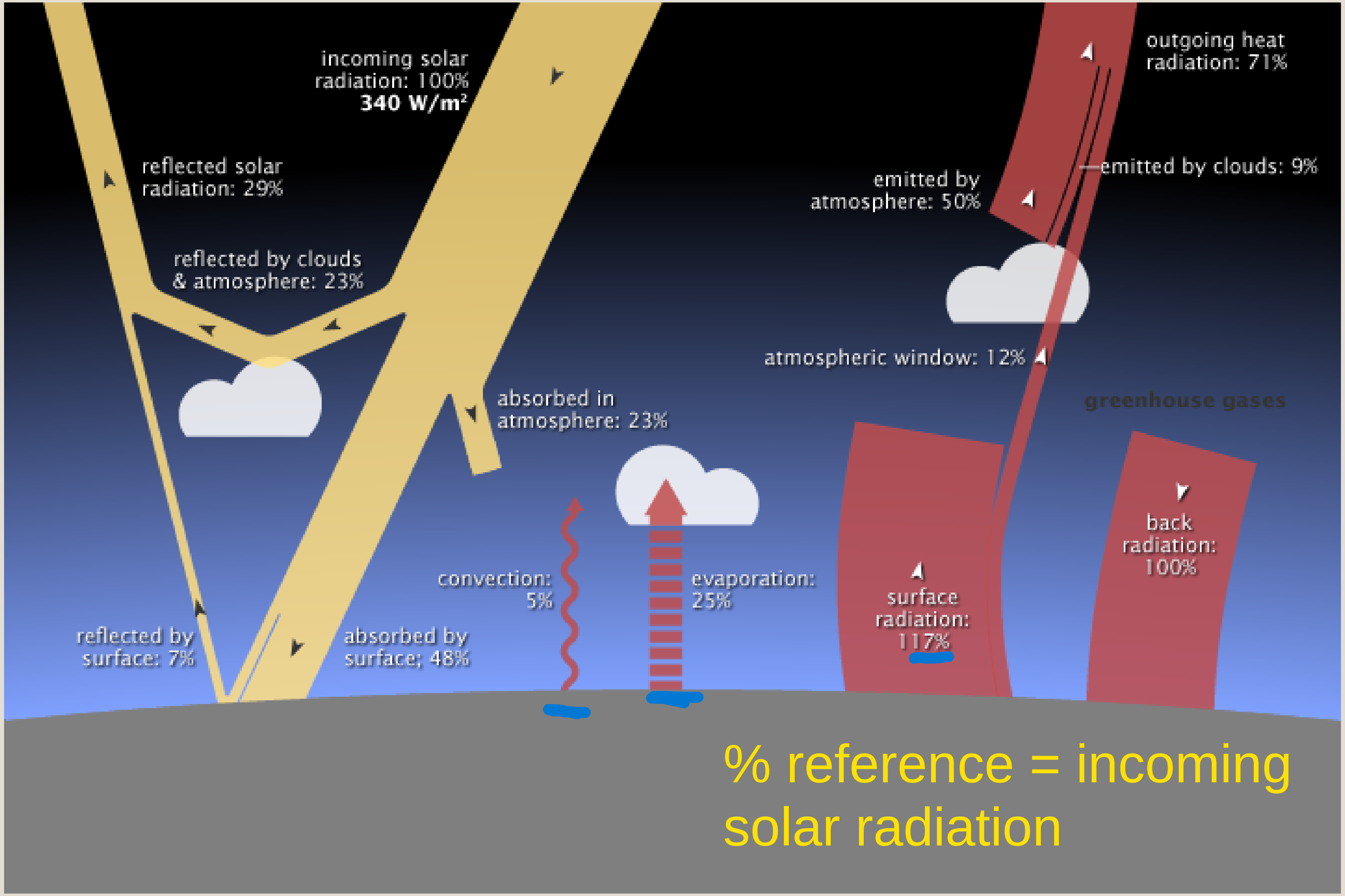
- **Carbon Cycle and Climate**:
  - The carbon cycle involves chemical transformations and regulates the concentrations of key greenhouse gases: carbon dioxide (CO_2) and methane (CH_4).
- **Carbon Reservoirs**:
  - Important carbon reservoirs include the **atmosphere, biosphere** (green plants, plankton, food web), and Earth's crust (**lithosphere**).
  - Atmospheric CO_2 is intermediate in size compared to the biospheric and crustal reservoirs.
- **Exchange Rates and Residence Times**:
  - Small reservoirs (atmosphere, biosphere) have much faster exchange rates than large reservoirs (Earth's crust).
  - Carbon in the Earth's crust has much longer residence times due to its larger size and slower exchange rates.

Table 2.3 Major carbon reservoirs in the Earth system and their present capacities in units of kg m^{-2} averaged over the Earth's surface and their residence times[a]

Reservoir	Capacity	Residence time
Atmospheric CO_2	1.6	10 years
Atmospheric CH_4	0.02	9 years
Green part of the biosphere	0.2	Days to seasons
Tree trunks and roots	1.2	Up to centuries
Soils and sediments	3	Decades to millennia
Fossil fuels	10	–
Organic C in sedimentary rocks	20,000	2×10^8 years
Ocean: dissolved CO_2	1.5	12 years
Ocean CO_3^{2-}	2.5	6,500 years
Ocean HCO^-	70	200,000 years
Inorganic C in sedimentary rocks	80,000	10^8 years

[a] Capacities based on data in Fig. 8.3 (p. 150) of Kump, Lee R.; Kasting, James F.; Crane, Robert G., The Earth System, 2nd Edition, © 2004. Adapted by permission of Pearson Education, Inc., Upper Saddle River, NJ.

Earth's Global Energy Balance



https://earthobservatory.nasa.gov/features/EnergyBalance

Earth's Global Energy Balance

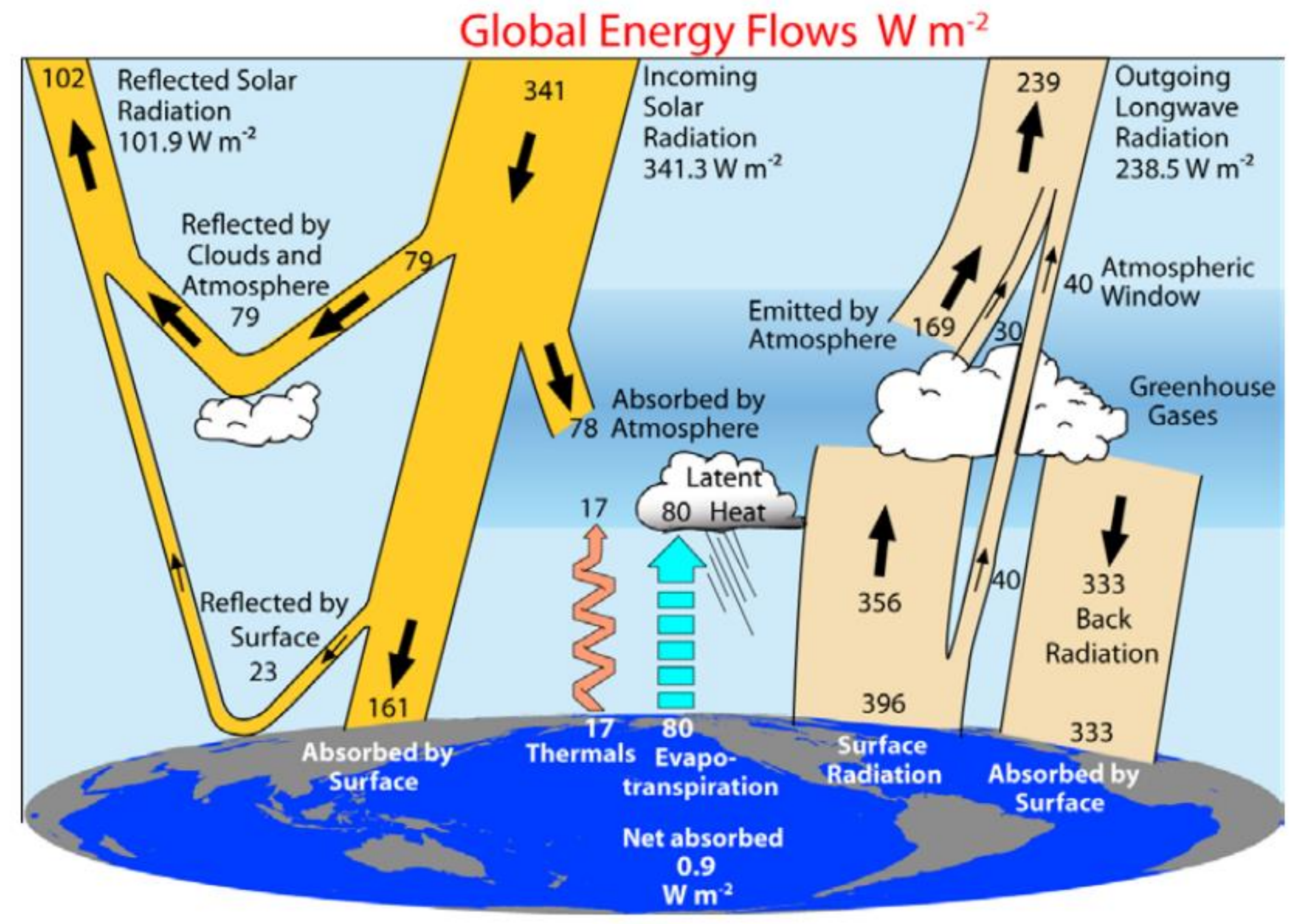
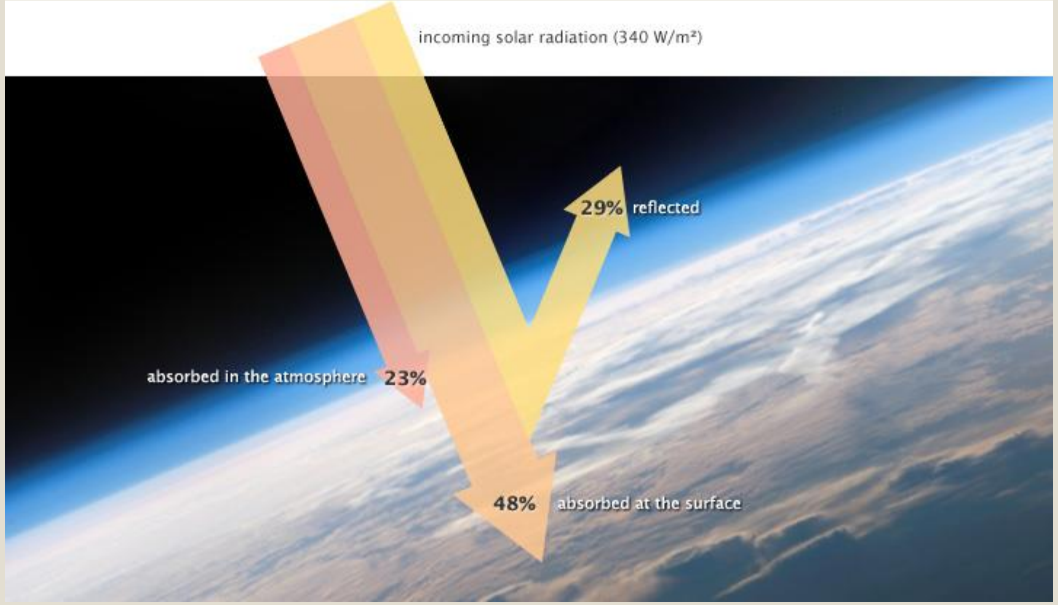


Fig. 2. The global annual mean Earth's energy budget for the March 2000 to May 2004 period in $W\,m^{-2}$. The broad arrows indicate the schematic flow of energy in proportion to their importance. From Trenberth et al.[6]

https://courses.seas.harvard.edu/climate/seminars/pdfs/Trenberth2009_TrackingGlobalEnergy.pdf

Earth's Energy Budget

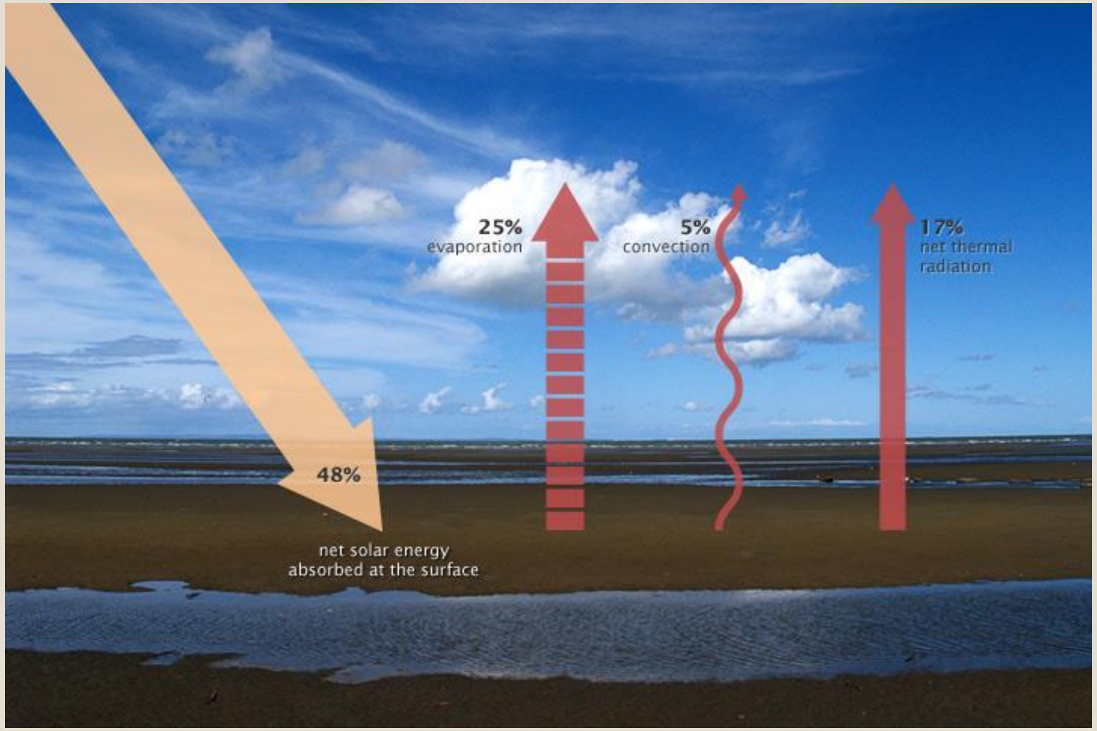
- **Earth's Heat Engine**:
  - Moves heat across the surface and from the surface/lower atmosphere to space.
  - This process is part of Earth's energy budget.
- **Energy Balance**:
  - For stable temperatures, incoming and outgoing energy must be equal (radiative equilibrium).
- **Solar Energy Distribution**:
  - 29% of incoming solar energy is reflected back to space by clouds, particles, and bright surfaces.
  - 23% is absorbed by the atmosphere (water vapor, dust, ozone).
  - 48% is absorbed by the Earth's surface.
  - In total, 71% of incoming solar energy is absorbed by the Earth system.



https://earthobservatory.nasa.gov/features/EnergyBalance

Surface Energy Budget

- **Energy Budget Levels**:
  - Energy balance involves three levels: Earth's surface, the edge of the atmosphere, and the atmosphere itself.
  - At each level, incoming and outgoing energy (net flux) must be equal.
- **Solar Energy Reflection and Absorption**:
  - 29% of incoming sunlight is reflected back to space by bright particles and surfaces.
  - 71% is absorbed: 23% by the atmosphere and 48% by the land and oceans.
- **Balancing Surface Energy**:
  - To balance the energy budget, the Earth's surface must release the 48% of absorbed solar energy.
  - Energy is released through evaporation, convection, and thermal infrared radiation.



https://earthobservatory.nasa.gov/features/EnergyBalance

Atmosphere Energy Budget

- Energy entering and leaving the Earth's surface and atmosphere must be balanced.
- The atmosphere radiates **thermal infrared energy equal to 59%** of incoming solar energy, indicating it absorbs the same amount.
- **Clouds, aerosols, water vapor, and ozone** absorb **23%** of incoming solar energy.
- **Evaporation and convection transfer 25% and 5%** of incoming solar energy from the surface to the atmosphere, respectively.
- These processes account for 53% of the incoming solar energy transferred to the atmosphere.
- The remaining **5-6% of energy comes from the Earth's surface** to balance the total energy inflow and outflow.

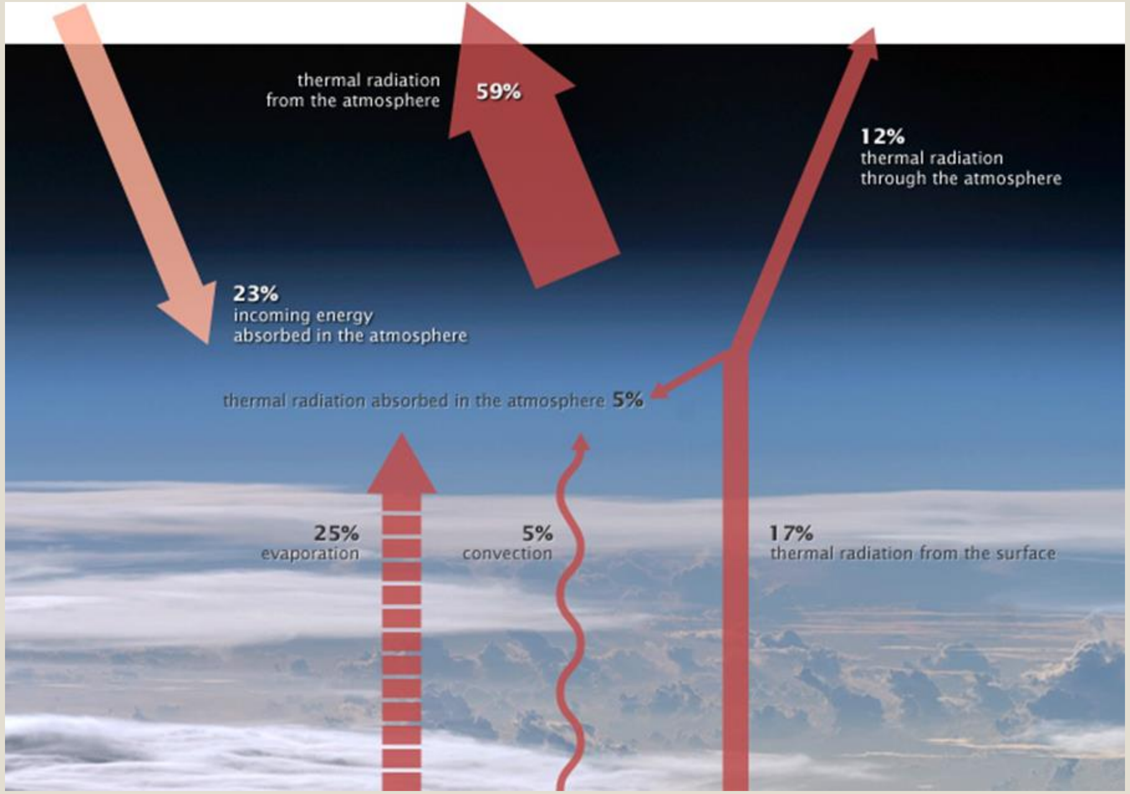
Natural Greenhouse Effect

Transparency of Gases:

- Major gases (oxygen and nitrogen) are transparent to both incoming sunlight and outgoing thermal infrared.
- Water vapor, carbon dioxide, methane, and other trace gases are opaque to many wavelengths of thermal infrared.

Thermal Infrared Radiation:

- The Earth's surface radiates 17% of incoming solar energy as thermal infrared.
- Only 12% of this energy escapes directly to space.
- The remaining 5-6% is absorbed by greenhouse gases, raising their temperature.



https://earthobservatory.nasa.gov/features/EnergyBalance

Natural Greenhouse Effect

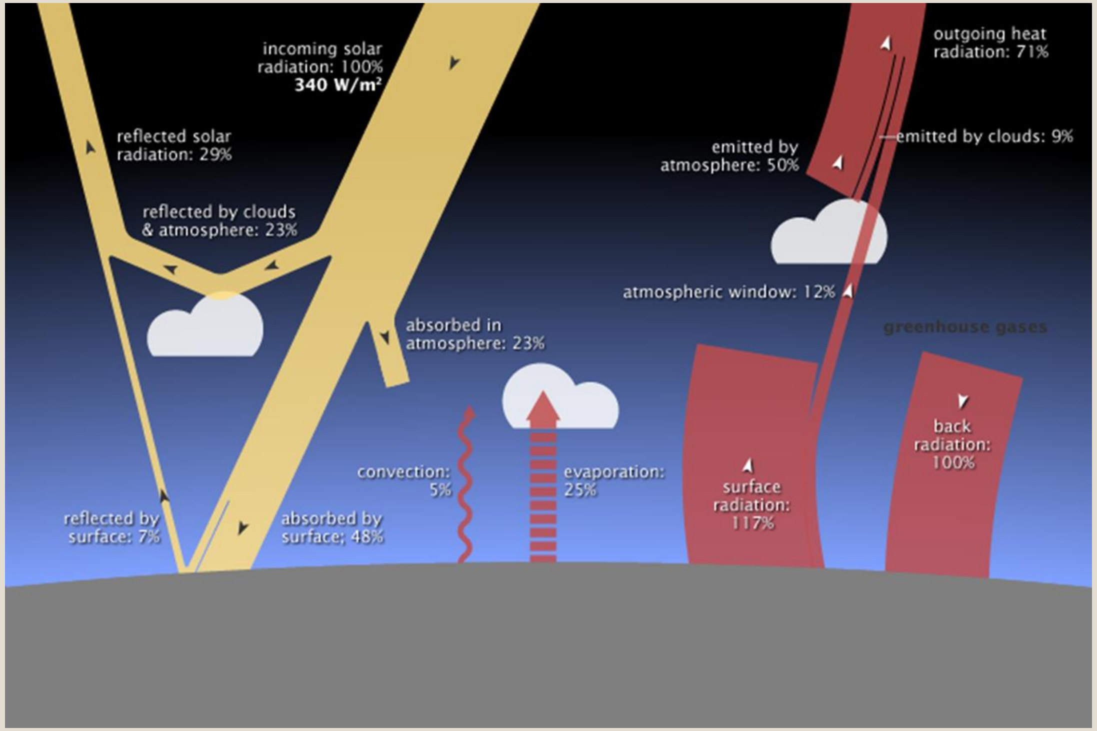
- **Absorption and Radiation**:
  - Greenhouse gases absorb thermal infrared energy, raising their temperature.
  - They radiate increased thermal infrared energy in all directions, similar to warm coals.
- **Heat Transfer**:
  - Heat radiated upward is repeatedly absorbed and re-radiated by greenhouse gases.
  - At altitudes of 5-6 km, greenhouse gas concentration is low enough for heat to escape freely to space.
- **Downward Radiation**:
  - Some radiated heat spreads downward, warming the Earth's surface.
  - This additional warming, beyond direct solar heating, is known as the natural greenhouse effect.

Effect on Surface Temperature

- **Temperature Increase**:
  - The natural greenhouse effect raises Earth's average surface temperature to about 15°C, which is over 30°C warmer than it would be without an [redacted] natural GH effect
- **Back Radiation**:
  - Heat radiated from the atmosphere to the surface, known as "back radiation," equals 100% of the incoming solar energy.
- **Surface Response**:
  - The Earth's surface temperature increases in response to this additional energy, beyond direct solar heating.

Effect on Surface Temperature

- **Surface Heat Release**:
  - As solar heating and atmospheric "back radiation" raise the surface temperature, the surface releases heat equivalent to 117% of incoming solar energy.
- **Net Upward Heat Flow**:
  - The net upward heat flow is 17% of incoming sunlight (117% released minus 100% back radiation).
- **Heat Transfer**:
  - Some heat escapes directly to space.
  - The rest is transferred through the atmosphere until the energy leaving the top matches the incoming solar energy.



https://earthobservatory.nasa.gov/features/EnergyBalance

Back Radiation

- **Back radiation** refers to the thermal infrared energy that is radiated from the atmosphere back to the Earth’s surface.
- Back radiation from the atmosphere to the Earth’s surface is equivalent to **100% of the incoming solar energy**. This means that the energy radiated back to the surface by greenhouse gases matches the total amount of solar energy that the Earth receives.
- **Absorption and Emission**: **Greenhouse gases in the atmosphere**, such as water vapor, carbon dioxide, and methane, **absorb thermal infrared energy** emitted by the Earth’s surface. These gases then **re-radiate this energy in all directions**, including back towards the surface.
- **Energy Balance**: This process is a crucial part of the Earth’s energy budget, helping to keep the surface warmer than it would be if only direct solar heating were involved.
- **Natural Greenhouse Effect**: Back radiation **contributes to the natural greenhouse effect**, which raises the Earth’s average surface temperature and makes the planet habitable.

Hydrosphere and Hydrologic Cycle

- **Hydrosphere and Water Cycling**:
  - Life on Earth relies on the cycling of water among various reservoirs, collectively known as the hydrosphere.
- **Residence Time Concept**:
  - Residence time is the mass of a substance in a reservoir divided by its efflux rate.
  - It indicates how long a typical molecule stays in a reservoir before moving to another.
- **Reservoir Size and Exchange Rates**:
  - Long residence times suggest large reservoirs or slow exchange rates, and vice versa.

Hydrosphere and Hydrologic Cycle

Table 2.2 Masses of the various reservoirs of water in the Earth system (in 10^3 kg m^{-2}) averaged over the surface of the Earth, and corresponding residence times

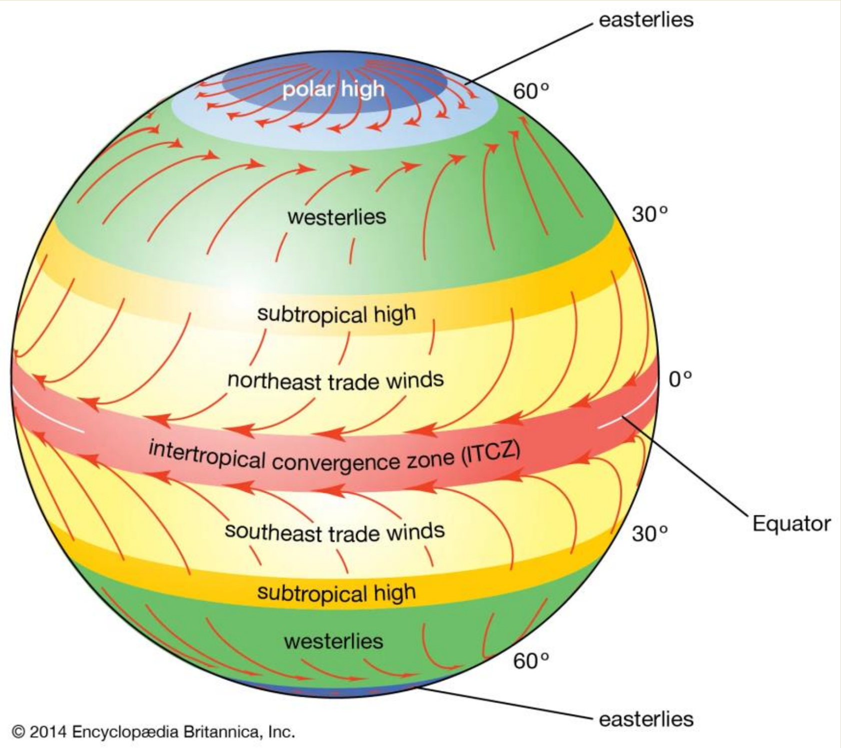
Reservoirs of water	Mass	Residence time
Atmosphere	0.01	Days
Fresh water (lakes and rivers)	0.6	Days to years
Fresh water (underground)	15	Up to hundreds of years
Alpine glaciers	0.2	Up to hundreds of years[a]
Greenland ice sheet	5	10,000 years[b]
Antarctic ice sheet	53	100,000 years
Oceans	2,700	
Crust and mantle	20,000	10^{11} years

[a] Estimated by dividing typical ice thicknesses of a large alpine glacier (~300 m) by the annual rate of ice accumulation (~1 m).
[b] Estimated by dividing typical ice thicknesses in the interior of the Greenland ice sheet (2000 m) by the annual rate of ice accumulation (~0.2 m).

- **Largest Water Reservoir**:
  - The **Earth's mantle** is the largest water reservoir.
  - Water expelled from the mantle through volcanic emissions is estimated at 2×10^{-4} kg/m²/year.
  - This results in a residence time of approximately 10^{11} years.
  - After the mantle and oceans, the next largest reservoir of water in the Earth system is the **continental ice sheets**, the volumes of which have varied widely on timescales of tens of thousands of years and longer, causing large variations in global sea level.

Hydrologic Cycle

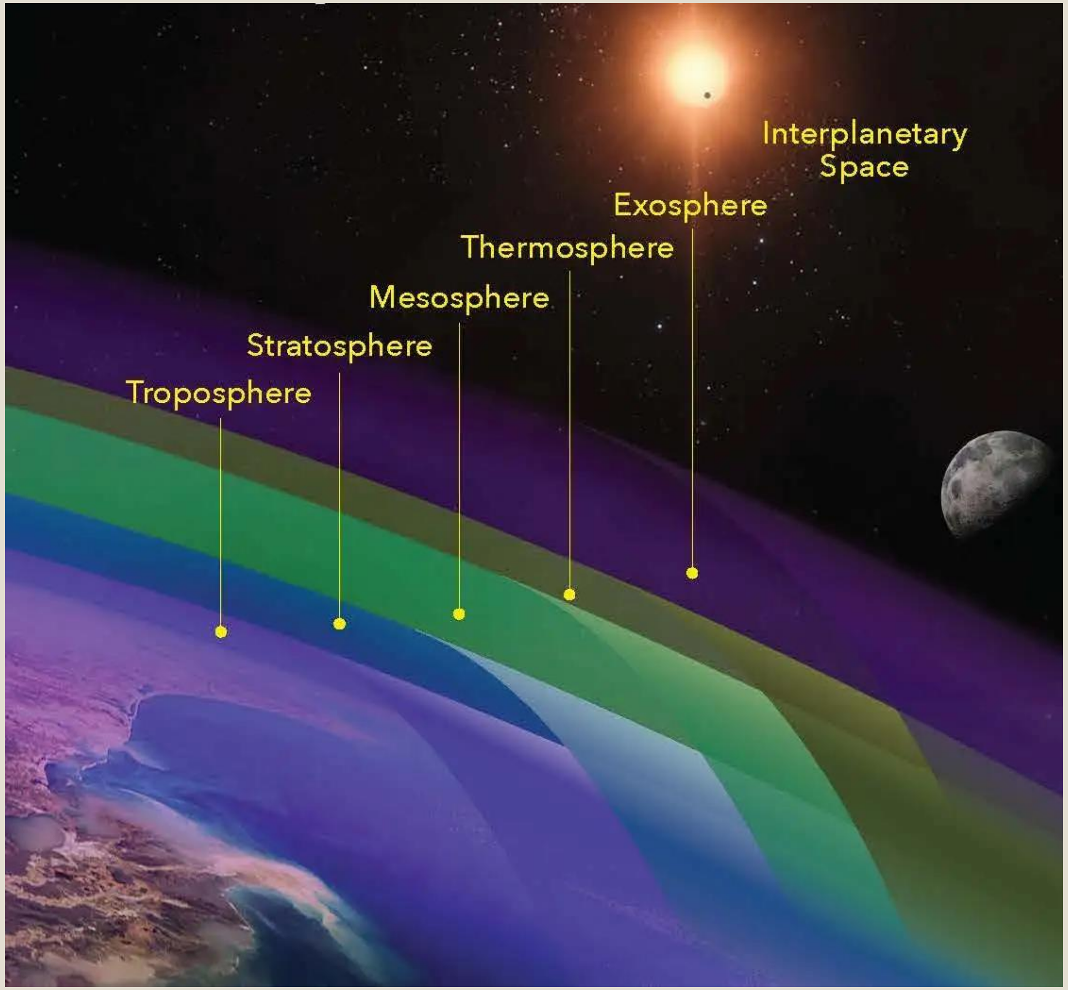
- The atmosphere, though the **smallest reservoirs of water** of the Earth system, has the **highest exchange rates** with other components.
- Water in the atmosphere has **a residence time** of about **10 days**. This is calculated by dividing the mass of atmospheric water (approximately 30 kg/m^2, or a 3 cm deep layer of liquid water) by the average global rainfall rate (around 1 meter per year or 0.3 cm per day).
- Averaged over the globe, **the rate of precipitation P** equals **the rate of evaporation E**.
- However, in analyzing **the water balance** for a limited region, the horizontal transport of water vapor by winds must also be considered. For example, within **the region of the Intertropical Convergence Zone (ITCZ)**, P >> E: the excess precipitation is derived from an influx of water vapor carried by the converging trade wind.



https://www.britannica.com/science/intertropical-convergence-zone

Atmosphere

- **Atmosphere**: The gaseous envelope of a celestial body (such as a planet) (Merriam Webster).
- There are **five main layers** that make up the atmosphere, differentiated by factors such as temperature, chemical composition, and air density.
  1. Troposphere
  2. Stratosphere
  3. Mesosphere
  4. Thermosphere
  5. Exosphere



https://www.nasa.gov/general/what-is-earths-atmosphere/#hds-sidebar-nav-2

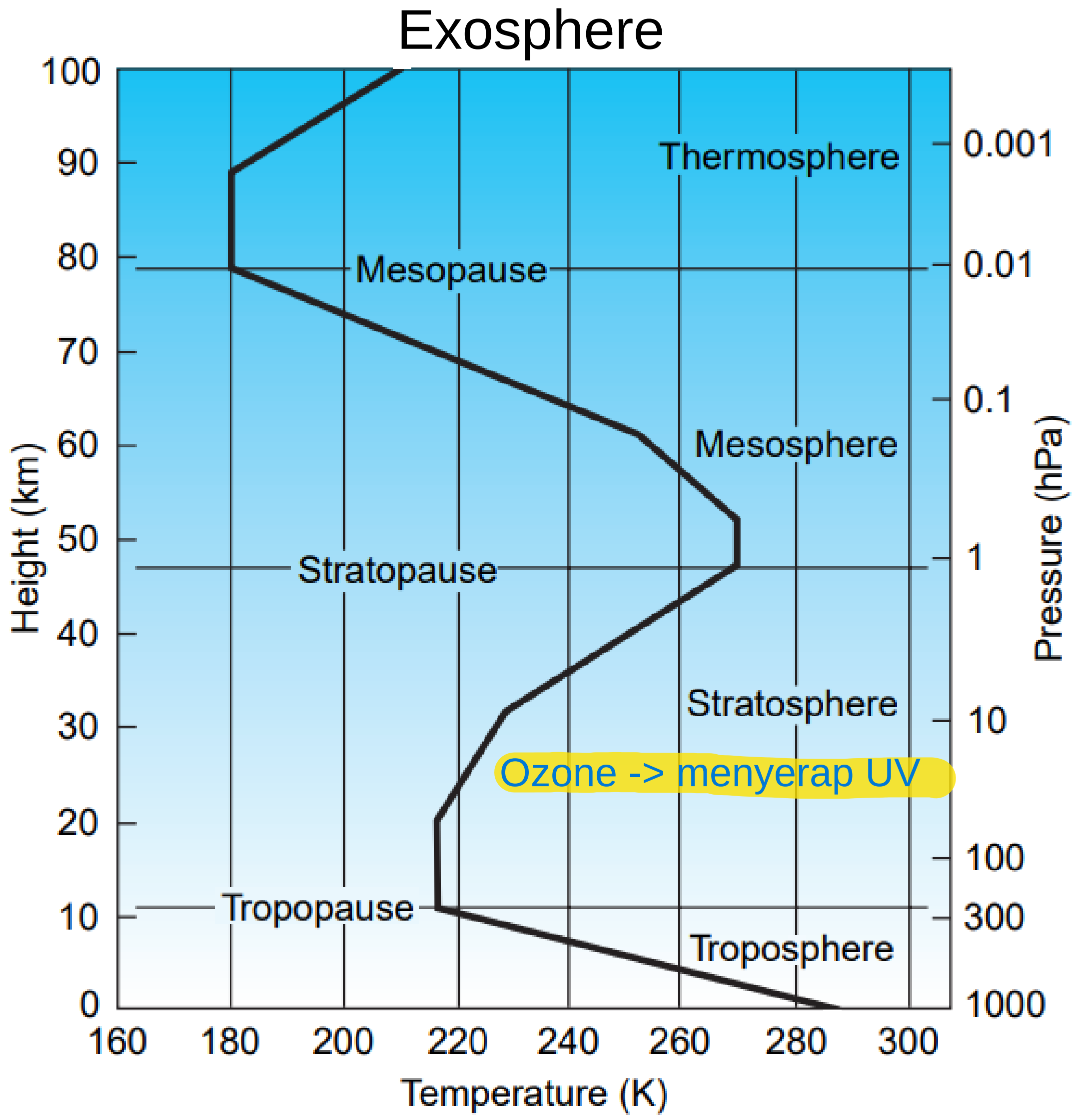


Fig. 1.9 A typical midlatitude vertical temperature profile, as represented by the U.S. Standard Atmosphere.

John M. Wallace and Peter V. Hobbs. Atmospheric Science, 2nd edition, 2006.

Cryosphere

- The term cryo- (frozen) sphere refers to components of the Earth system comprised of **water in its solid state**, or in which **frozen water** is an **essential component**.
- The cryosphere contributes to the thermal inertia of the climate system; it contributes to the **reflectivity or albedo of the Earth**; by taking up and releasing fresh water in the polar regions, it influences **oceanic thermohaline circulation**; and it stores enough water to significantly the **influence global sea level**.

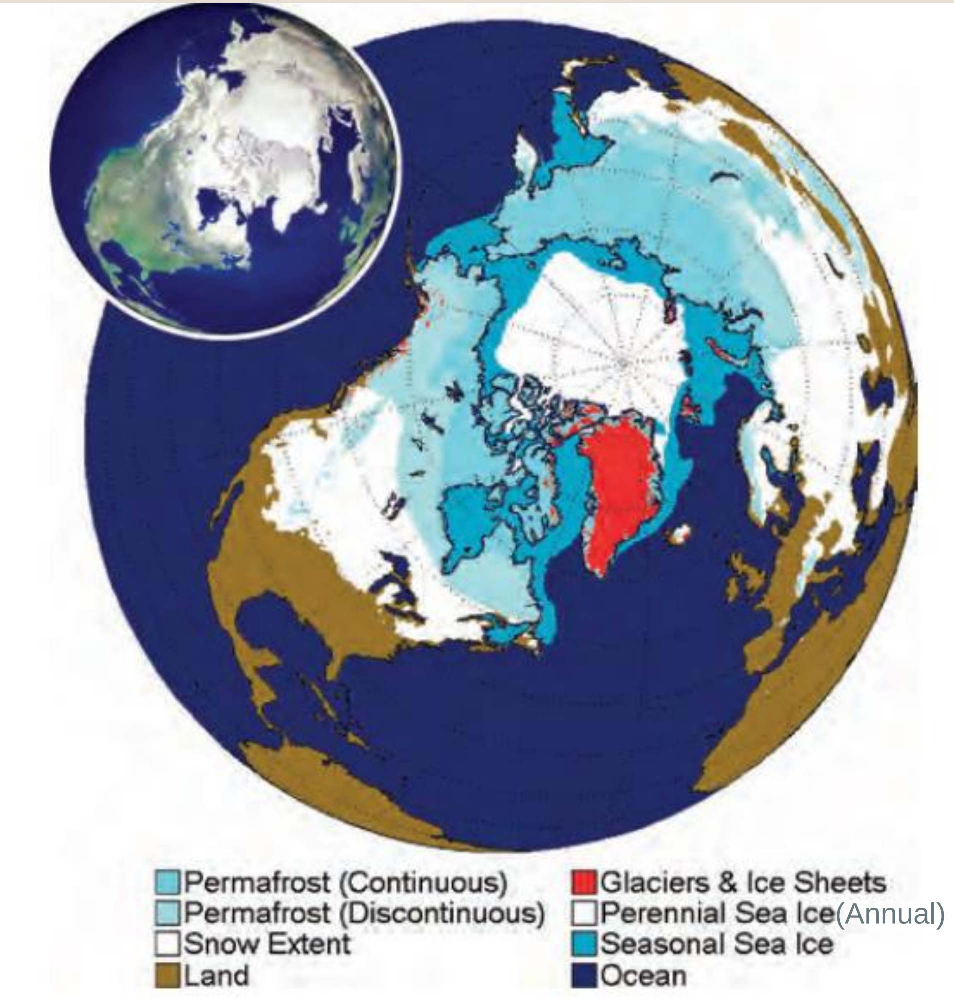


Fig. 2.12 Elements of the northern hemisphere cryosphere. The equatorward edge of the snow cover corresponds to ~50% coverage during the month of maximum snow extent. [Courtesy of Ignatius Rigor.] The inset at the upper left shows a NASA RADARSAT image highlighting these features.

John M. Wallace and Peter V. Hobbs. Atmospheric Science, 2nd edition, 2006.

Cryosphere

- The continental ice sheets, dominated by **Antarctica** and **Greenland**, are the most massive elements of the cryosphere.
- Over periods of tens of thousands of years and longer, annual layers of snow that fall in the relatively flat interior of the ice sheets are compressed by the accumulation of new snow on top of them. As the pressure increases, snow is transformed into ice.
- Due to the dome-like shape of the ice sheets and the plasticity of the ice itself, the compressed layers of ice gradually creep downhill toward the periphery of the ice sheet, causing the layer as a whole to **spread out horizontally** and **to thin in the vertical dimension**.

Table 2.1 Surface area and mass of the various components of the cryosphere[a]

Cryospheric component	Area	Mass
Antarctic ice sheet	2.7	53
Greenland ice sheet	0.35	5
Alpine glaciers	0.1	0.2
Arctic sea ice (March)	3	0.04
Antarctic sea ice (September)	4	0.04
Seasonal snow cover	9	<0.01
Permafrost	5	1

[a] Surface area is expressed as percentage of the area of the surface of the Earth. Mass is expressed in units of 10^3 kg m^{-2} (numerically equivalent to meters of liquid water) averaged over the entire surface area of the Earth. For reference, the total surface area of the Earth and the area of the Earth covered by land are 5.12 and 1.45 $\times 10^{14}$ m^2, respectively. [Courtesy of S. G. Warren.]

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Cryosphere

- Along the divides of the ice sheets the movement is very slow and the layering of the ice is relatively undisturbed. In ice cores extracted from these regions, the **age of the ice** increases monotonically with depth to **100,000 years in the Greenland ice sheet** and **over 500,000 years in the Antarctic ice sheet**.
- In many respects**, alpine (i.e., mountain) glaciers** behave like continental ice sheets, but they are much smaller in areal coverage and mass. Parcels of ice within them flow continually downhill from an upper dome-like region where snow and ice accumulate toward their snouts where mass is lost continually due to melting. Because of their much smaller masses, glaciers **respond much more quickly to climate change than continental ice sheets**, and ice cycles through them much more rapidly.

Cryosphere

- **Sea ice** covers a larger area of the Earth's surface area than the continental ice sheets but, with **typical thicknesses of only 1–3 m**. The ice is not a continuous surface, but a fractal field comprised of ice floes (pieces) of various of shapes and sizes.
- **Land snow cover** occupies an even larger area of the northern hemisphere than sea ice and it **varies much more widely from week to week and month to month** than does sea ice. With the warming of the land surface during spring, the snow virtually disappears, except in the higher mountain ranges.

John M. Wallace and Peter V. Hobbs. Atmospheric Science, 2nd edition, 2006.

Cryosphere

- **Permafrost** is a layer of soil that remains frozen for at least two consecutive years.
- Permafrost embedded in soils profoundly influences terrestrial ecology and human activities over large areas of **Siberia, Alaska, and northern Canada**.
- Even in the zone of continuous permafrost, the **topmost few meters of the soil thaw** during **summer** in response to the downward diffusion of heat from the surface. The upward diffusion of heat from the Earth's interior limits the vertical extent of the permafrost layer.

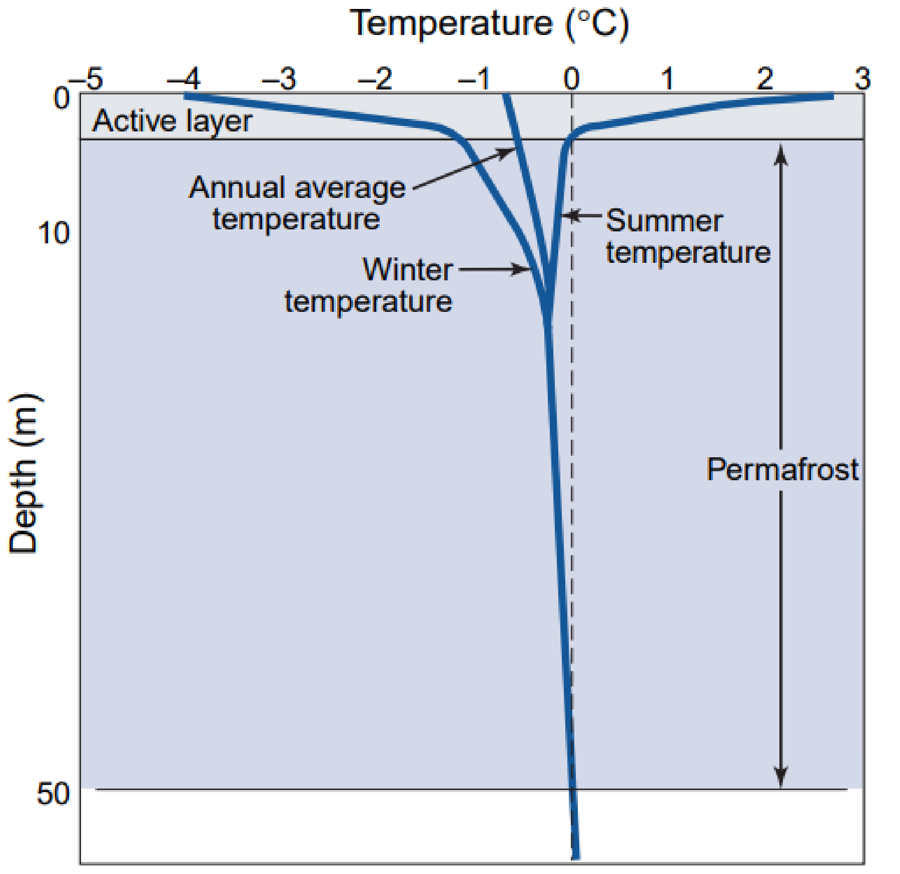

Fig. 2.17 Schematic vertical profile of summer and winter soil temperatures in a region of permafrost. The depth of the permafrost layer varies from as little as a few meters in zones of intermittent permafrost to as much as 1 km over the coldest regions of Siberia.

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Geosphere / Lithosphere

- Earth's three main geological layers can be categorized by chemical composition or the chemical makeup: **crust, mantle, and core**.
- The **crust** is the **outermost layer** and composed of mostly silicon, oxygen, aluminum, iron, and magnesium.
- There are two types, **continental crust** and **oceanic crust**.
- **Continental crust** is about 50 km (30 mi) thick, composed of low-density igneous and sedimentary rocks.
- **Oceanic crust** is approximately 10 km (6 mi) thick and made of high-density igneous basalt-type rocks. Oceanic crust makes up most of the ocean floor, covering about 70% of the planet.

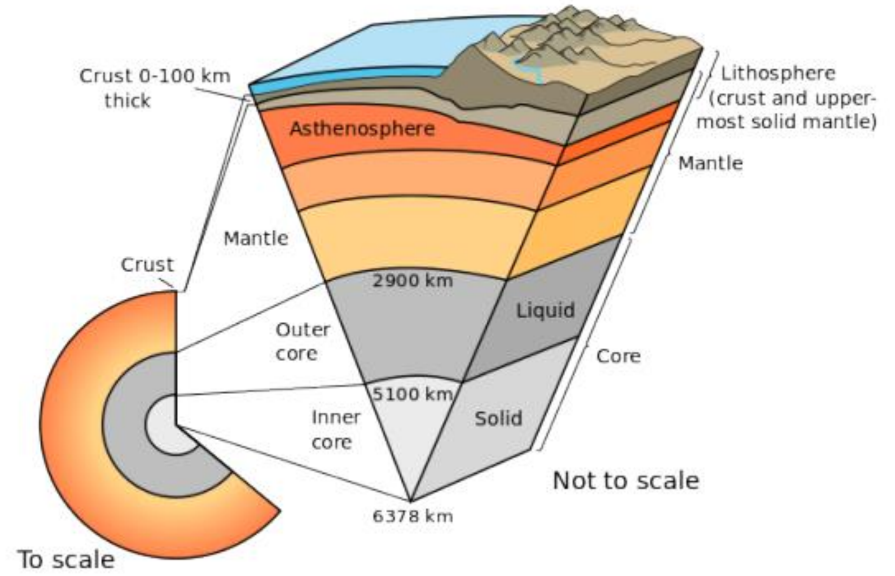

Figure 1.27: The layers of the Earth. Physical layers include lithosphere and asthenosphere; chemical layers are crust, mantle, and core.

Laura Neser, 2023. Introduction to Earth Science.

Geosphere / Lithosphere

- **Tectonic plates** are made of **crust** and a portion the **upper mantle**, forming a rigid physical layer called **the lithosphere**.
- The mantle is the largest chemical layer by volume, located below the crust. It extends down to about 2,900 km (1,800 mi) beneath the Earth's surface.
- The upper mantle is very hot and flexible, allowing tectonic plates to float and move on it.
- Below the mantle lies the Earth's core, which is 3,500 km (2,200 mi) thick. The core is composed of iron and nickel.
- The core consists of two parts: a liquid outer core and a solid inner core.

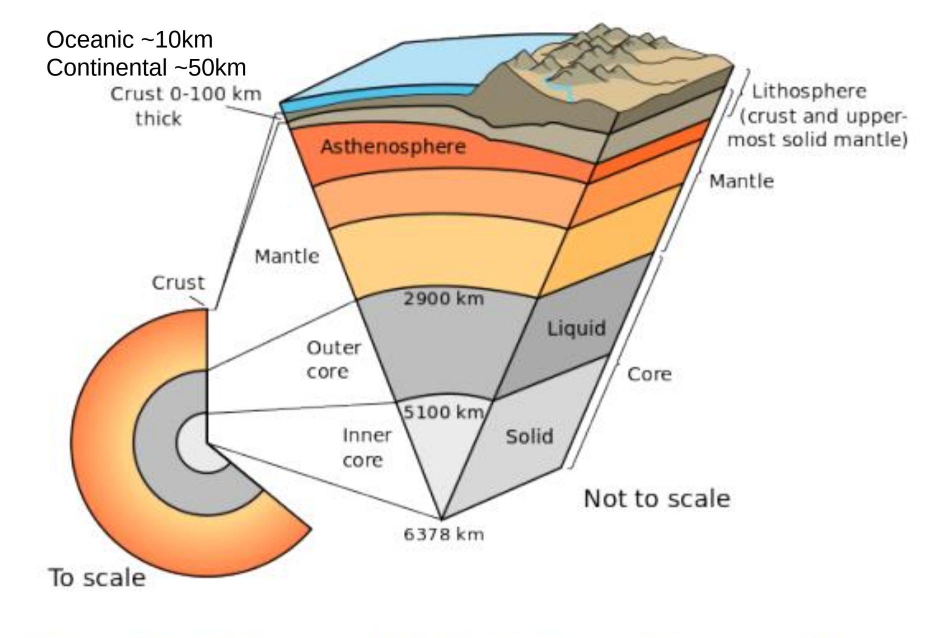

Figure 1.27: The layers of the Earth. Physical layers include lithosphere and asthenosphere; chemical layers are crust, mantle, and core.

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Biosphere

- The Biosphere is **Earth's zone of life**. Every organism on Earth belongs to the biosphere.
- The **biosphere** is the global sum of all ecosystems, encompassing all living organisms and their interactions with the elements of the lithosphere (land), hydrosphere (water), and atmosphere (air).
- Biosphere includes all life forms, from microorganisms to plants and animals, and the environments they inhabit
- **Importance of biosphere**: biodiversity, resources and ecosystem services.
- **Biodiversity**: It supports a vast diversity of life forms, contributing to ecosystem stability and resilience 2.
- **Resources**: Provides essential resources such as food, medicine, and raw materials for human use 2.
- **Ecosystem services**: Offers vital services like pollination, waste decomposition, and water purification

https://www.britannica.com/science/biosphere
https://www.nationalgeographic.org/encyclopedia/biosphere/

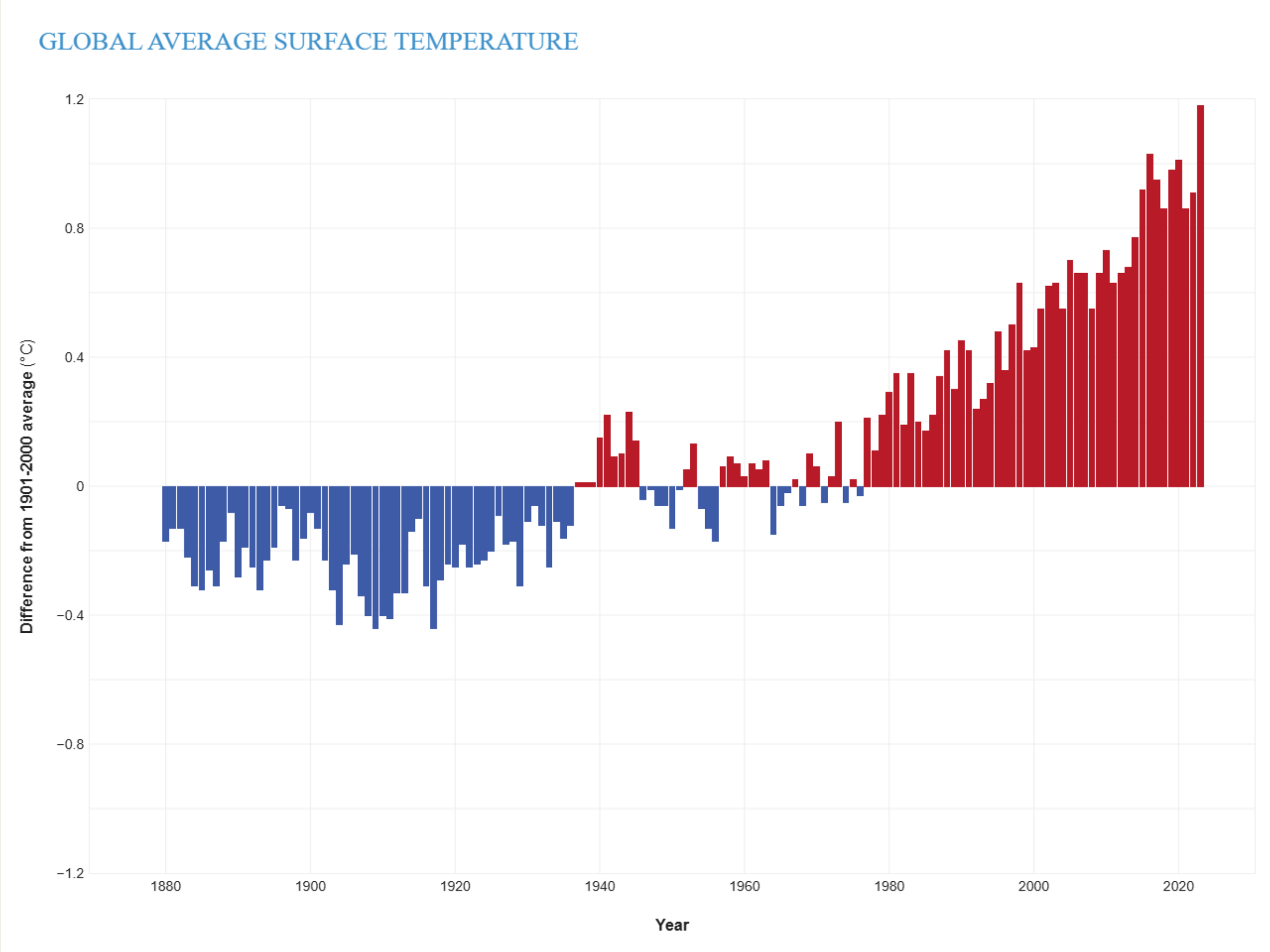
Biosphere

1. **Natural Biosphere**:
   1. **Terrestrial Biosphere**: Includes all land-based ecosystems such as forests, grasslands, deserts, and tundra.
   2. **Aquatic Biosphere**: Encompasses all water-based ecosystems, which can be further divided into:
      1. **Freshwater Ecosystems**: Rivers, lakes, streams, and wetlands.
      2. **Marine Ecosystems**: Oceans, coral reefs, and estuaries.
2. **Artificial Biosphere**:
   1. **Biosphere 2**: A man-made, closed ecological system in Arizona designed for research and experimentation.
   2. **BIOS-3**: A Soviet-era closed ecosystem in Siberia used for studying life support systems.

Biosphere 2

https://i.ytimg.com/vi/uzVhZCiROOI/maxresdefault.jpg

Global Warming



https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature

- Yearly surface temperature from 1880–2023 compared to the 20th-century average (1901-2000).
- Blue bars indicate cooler-than-average years; red bars show warmer-than-average years.

Global Warming

- ✓Earth's temperature has risen by an average of 0.11° Fahrenheit (0.06° Celsius) per decade since 1850, or about 2° F (= 1°C) in total.
  - The rate of warming since 1982 is more than three times as fast: 0.36° F (0.20° C) per decade.
- ✓2023 was the warmest year since global records began in 1850 by a wide margin.
  - It was 2.12 °F (1.18 °C) above the 20th-century average of 57.0°F (13.9°C).
  - It was 2.43 °F (1.35 °C) above the pre-industrial average (1850-1900).
- ✓The 10 warmest years in the historical record have all occurred in the past decade (2014-2023).

Expected Temperature Rise

- If you add to the blanket, expect to get warmer
- How much warmer?
  - Historically we have a 7°C effect from CO_2
  - Have gone from 280 to 400 ppm (10/7 times as much, or 3/7 increase)
  - This should translate into $7° \times 3/7$ = 3°C change
    - but takes some time because oceans are slow to respond, having *enormous* heat capacity
- Should be NO SURPRISE that burning loads of fossil fuels makes us warmer
  - not actually hard to understand!

Predicted Temperature Changes

- The IPCC predicts an increase of 1.1°C to 6.4°C from 1990 to 2100 depending on scenario.
- Earth can be slow to respond, due to thermal sink of oceans, and this lag means the temperature will continue to rise even if we ceased burning fossil fuels today.
- CO_2 hangs around long enough that we would likely not see the end of changes until ~2300 – this is under scenario that we STOP fossil fuels tomorrow.

Predicted Temperature Changes

- Thermal expansion of water plus glacial and polar ice-cap melting raise the sea level.
- The oceans are predicted to rise something like half-a-meter by 2100, maybe as much as 1 meter – goodbye to much of Bangladesh, much of the Nile valley, Louisiana.
- It will not stabilize until maybe 2300, by which time the rise could be several meters. This is even if we stop the CO_2 production today .

International Commitment to Climate Change

- **IPCC (Intergovernmental Panel on Climate Change)**

The IPCC is a **United Nations body** responsible for **assessing the science related to climate change**. Established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP), it **provides policymakers** with regular scientific assessments on climate change, its implications, and potential future risks, as well as proposing adaptation and mitigation strategies.

- **UNFCCC (United Nations Framework Convention on Climate Change)**

The UNFCCC is an international environmental treaty adopted in 1992 at the Earth Summit in Rio de Janeiro. Its main goal is to **stabilize greenhouse gas concentrations in the atmosphere** to prevent dangerous anthropogenic interference with the climate system. The treaty provides a framework for negotiating specific **international treaties** (called "protocols" or "agreements") that may **set binding limits on greenhouse gases**.

https://climatechampions.unfccc.int/the-ipcc-just-published-its-summary-of-5-years-of-reports-heres-what-you-need-to-know/

https://unfccc.int/process-and-meetings/what-is-the-united-nations-framework-convention-on-climate-change

International Commitment to Climate Change

- **Kyoto Protocol**

The Kyoto Protocol is an **international treaty** that extends the UNFCCC. Adopted in 1997 and entered into force in 2005, it commits its Parties by setting **internationally binding emission reduction targets**. The Protocol places a heavier burden on developed nations under the principle of "common but differentiated responsibilities" because they are largely responsible for the current high levels of greenhouse gas emissions in the atmosphere.

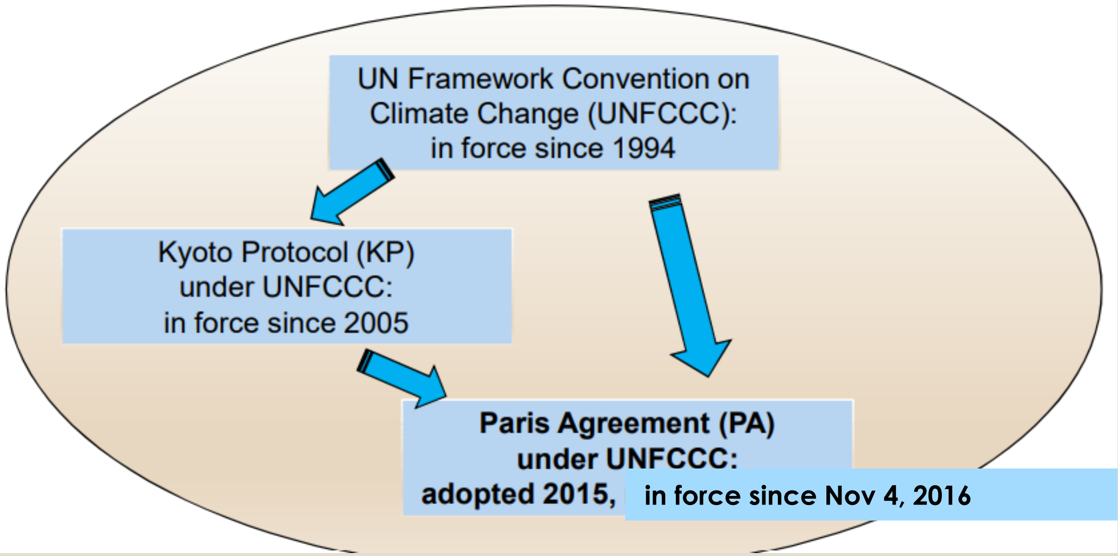
- **Paris Agreement**

The Paris Agreement is a **legally binding international treaty on climate change** adopted in 2015 during COP21 in Paris. It aims to **limit global warming to well below 2°C**, **preferably to 1.5°C**, compared to pre-industrial levels. The agreement works on a five-year cycle of increasingly ambitious climate action carried out by countries. It requires all Parties to put forward their best efforts through **nationally determined contributions (NDCs)** and to strengthen these efforts in the years ahead.

https://www.climate.gov/news-features/understanding-climate/what-cop
https://unfccc.int/kyoto_protocol
https://unfccc.int/process-and-meetings/the-paris-agreement

UNFCCC, COP, Protocols

International climate change regime: UNFCCC and its legal instruments



International climate change regime: evolution from Rio (1992) to Paris (2015)

UNFCCC (Climate Change Convention), with 196 "Parties":

- one of the three "Rio Conventions", adopted at "Rio Earth Summit" (1992); entered into force in 1994
- ultimate aim = preventing "dangerous" human interference with the climate system

Two major groups of Parties under the UNFCCC:

- Annex I Parties ("developed countries")
- Non-Annex I Parties ("developing countries")

Kyoto Protocol, with 192 Parties:

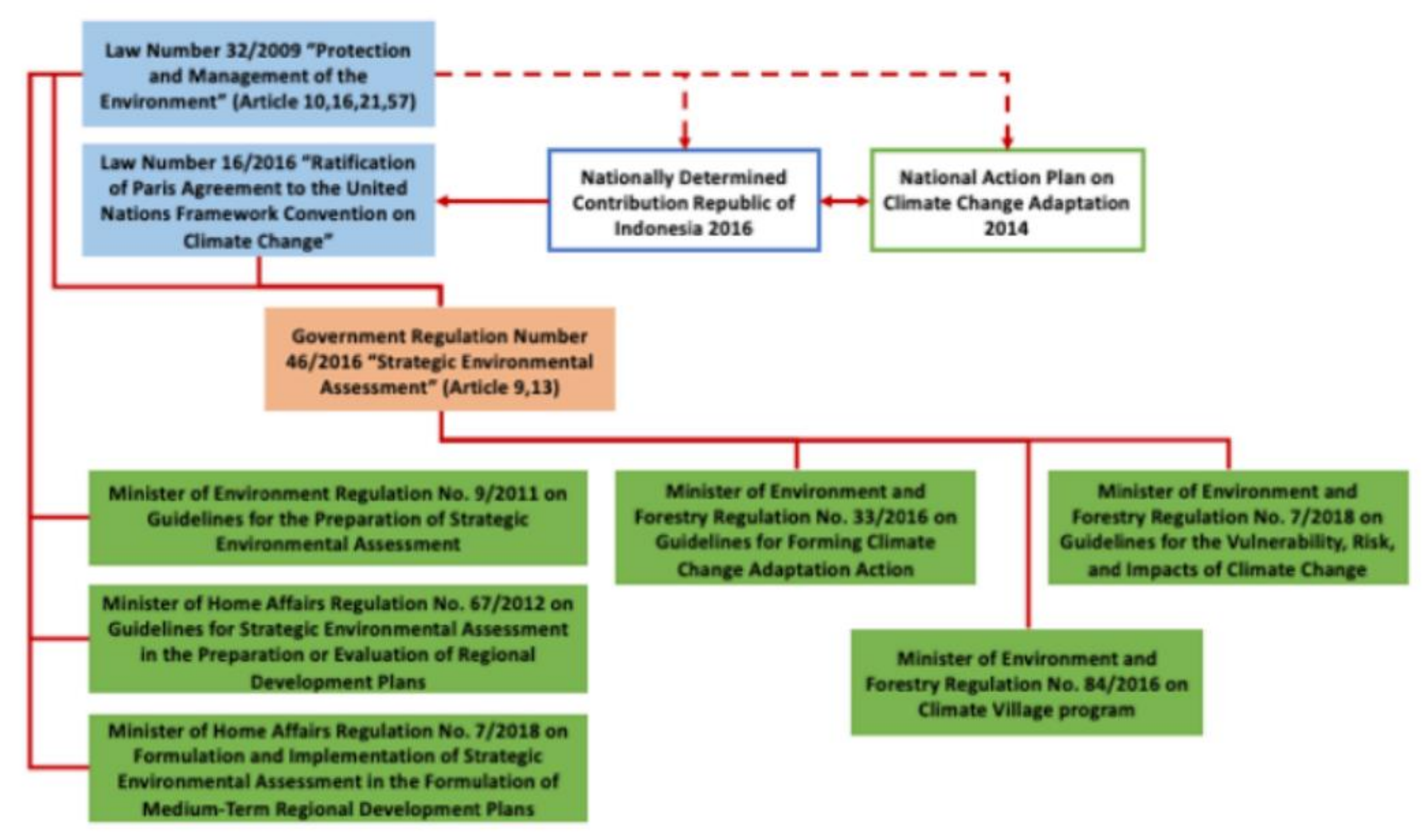
- a "Protocol" to the Convention, adopted in Kyoto, Japan, in 1997; entered into force in 2005
- introduced legally-binding targets/commitments to reduce/limit GHG emissions and more stringent reporting/review requirements
- these targets and rules apply only to Annex I countries

Paris Agreement (Paris, 2015):

- adopted in 2015, already signed by more than 180 countries
- not yet legally in force; conditions for entry into force to be fulfilled: ratification by 55 countries accounting for 55% of global emissions
- agreement for all Parties, with flexibility for developing countries

https://unfccc.int/

National Policy And Regulatory Framework Supporting Climate Change



Enhanced Nationally Determined Contribution Republic of Indonesia 2022

https://unfccc.int/sites/default/files/NDC/2022-09/23.09.2022_Enhanced%20NDC%20Indonesia.pdf#:~:text=ign%20with%20the%20Paris%20Agreement%20temperature%20goal%20by%20the%20end

CLEANER TECHNOLOGIES

Sheila Tobing

Energy Resources

Shale oil

CBM
Shale gas

Fossil

$CO_2 \leftarrow$ <u>Coal</u> $\leftarrow$ <u>Oil</u> $\rightarrow$ <u>Natural Gas</u> $\rightarrow H_2O$

dirty

clean

H/C =1	H/C=2	H/C=4
(s)	(l)	(g)

New energy -> Nuclear

Renewable: Biomass, Solar, Hydro, Geothermal, Wind, Ocean

Coal Bed Methane (CBM): a form of natural gas extracted from coal beds

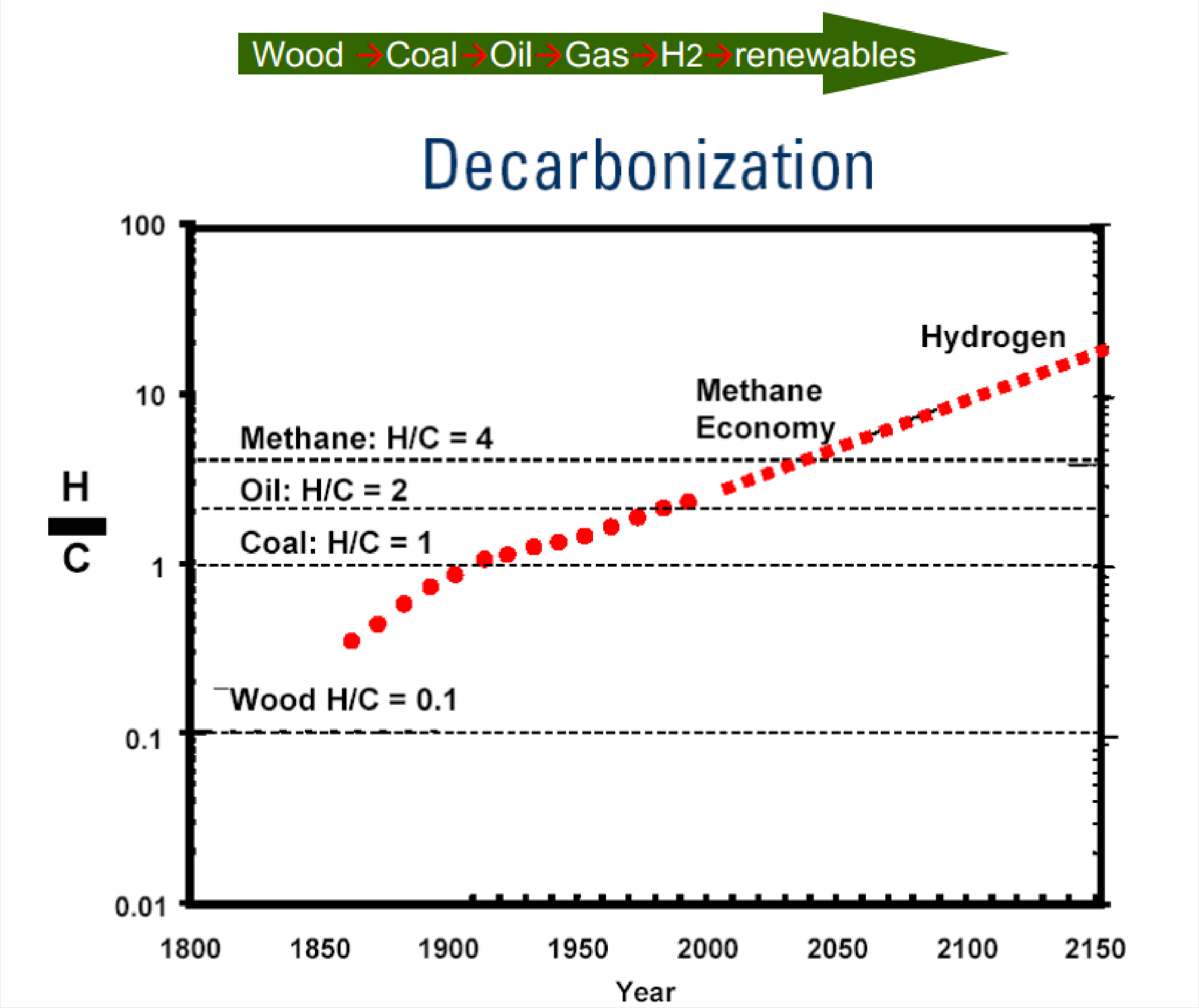
Hydrogen to Carbon Ratio

The **hydrogen-to-carbon (H/C) ratio** is a key indicator of the cleanliness of a fuel. Here's why:

- **Higher H/C Ratio**: Fuels with a higher hydrogen-to-carbon ratio tend to produce fewer carbon emissions when burned. For example, methane (CH_4) has a higher H/C ratio (4:1) compared to coal, which has a much lower H/C ratio. This means methane combustion releases less carbon dioxide (CO_2) per unit of energy produced.
- **Lower H/C Ratio**: Fuels with a lower hydrogen-to-carbon ratio, like coal, produce more CO_2 and other pollutants. This is because more carbon atoms are present in the fuel, leading to higher carbon emissions when the fuel is burned.
- **Cleanliness and Efficiency**: Hydrogen itself, with an H/C ratio of infinity (since it has no carbon), is considered a very clean fuel because its combustion produces only water vapor and no CO_2.

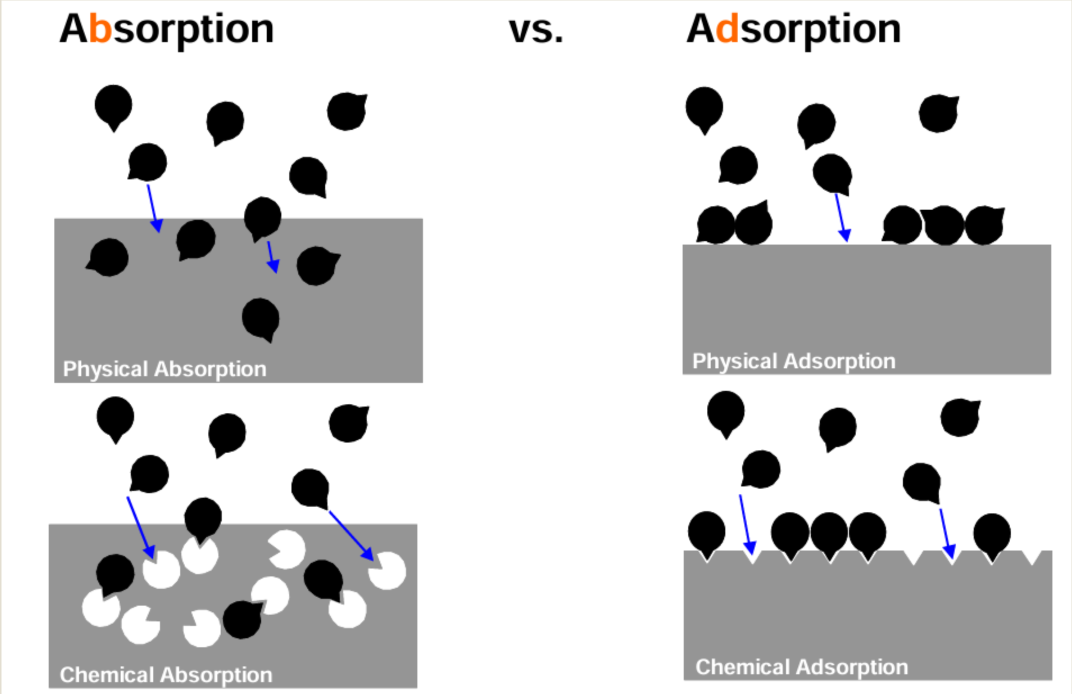
https://climate.mit.edu/ask-mit/how-clean-green-hydrogen

Hydrogen to Carbon Ratio



Cleaner Fossil Fuel Technology

- Reforming/Gasification
- Carbon Capture, Utilization and Storage
  - ✓ Pre-combustion
  - ✓ Post-combustion
  - ✓ Oxyfuel Combustion



Reforming / Gasification

- **Gasification Process**:
  - Converts carbon-based materials (e.g., coal) into synthesis gas (syngas).
  - Occurs in a high temperature/pressure vessel called a gasifier.
  - Involves chemical reactions with oxygen (or air) and steam, producing syngas and ash/slag.
- **Syngas Composition and Uses**:
  - Mainly consists of carbon monoxide (CO) and hydrogen (H2).
  - Can be converted to hydrogen and carbon dioxide (CO2) using a water-gas-shift reactor.
  - Hydrogen from syngas can generate electricity with no CO2 emissions.
  - Used in refining oil, producing ammonia and fertilizers, and making gasoline and diesel fuel.

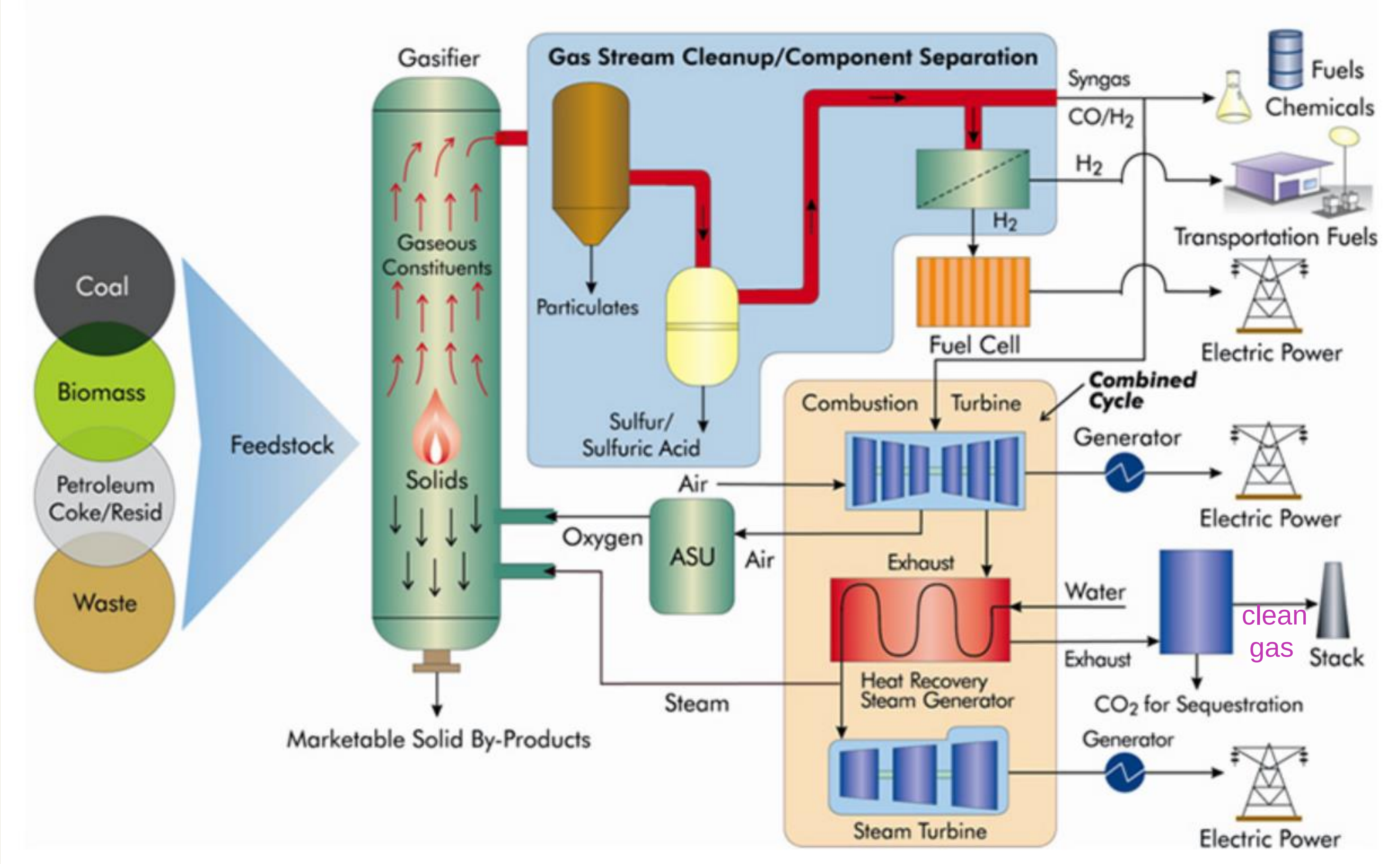
https://www.netl.doe.gov/research/Coal/energy-systems/gasification/gasifipedia/intro-to-gasification#:~:text=Gasification%20is%20a%20technological%20process%20that%20can%20convert%20any%20carbonaceous

Reforming / Gasification

- **Polygeneration and Carbon Capture**:
  - Gasification enables polygeneration plants to produce multiple products.
  - Efficiently captures CO2 from syngas, preventing greenhouse gas emissions.
  - CO2 can be used for Enhanced Oil Recovery or safely stored.
- **Advantages of Gasification**:
  - Offers an alternative to traditional methods of converting feedstocks into electricity and other products.
  - Particularly beneficial for clean electricity generation from coal.
  - Stable price and abundant supply of coal make it a preferred feedstock.

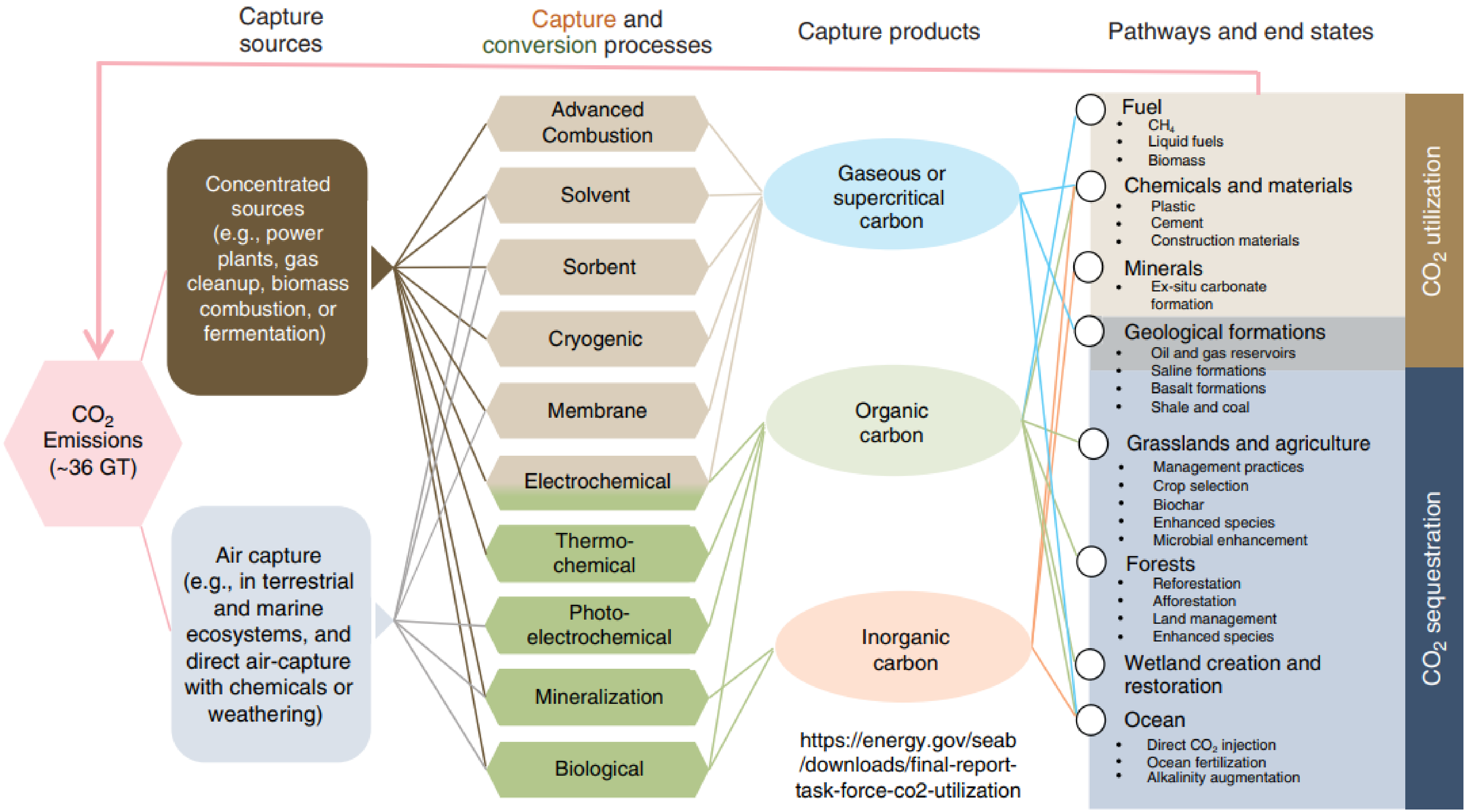
https://www.netl.doe.gov/research/Coal/energy-systems/gasification/gasifipedia/intro-to-gasification#:~:text=Gasification%20is%20a%20technological%20process%20that%20can%20convert%20any%20carbonaceous

Reforming / Gasification



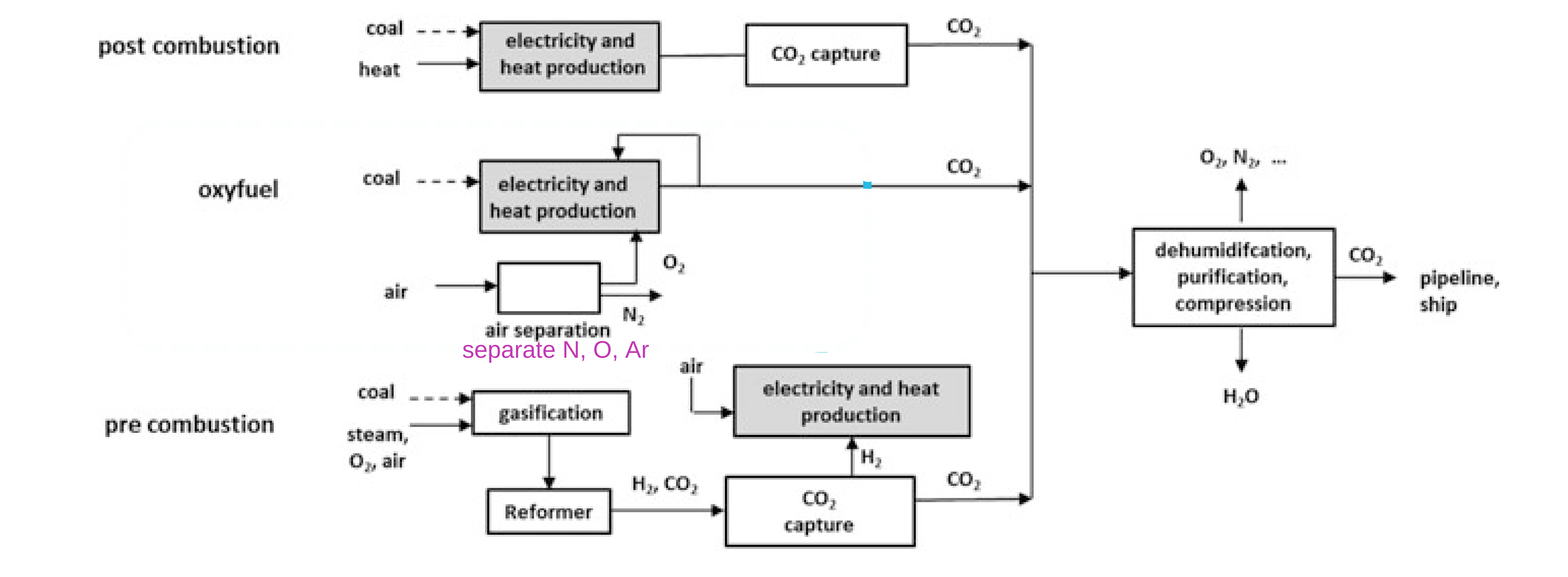
https://www.netl.doe.gov/research/Coal/energy-systems/gasification/gasifipedia/intro-to-gasification#:~:text=Gasification%20is%20a%20technological%20process%20that%20can%20convert%20any%20carbonaceous

CCUS



Modified from SEAB Report, 2016. CO_2 Utilization and Negative Emissions

General Principle of CCS Technologies



Source: Carbon Capture, Storage and Use Technical, Economic, Environmental and Societal Perspectives, Wilhelm

Carbon Capture - Chemical Looping (Pre-Combustion)

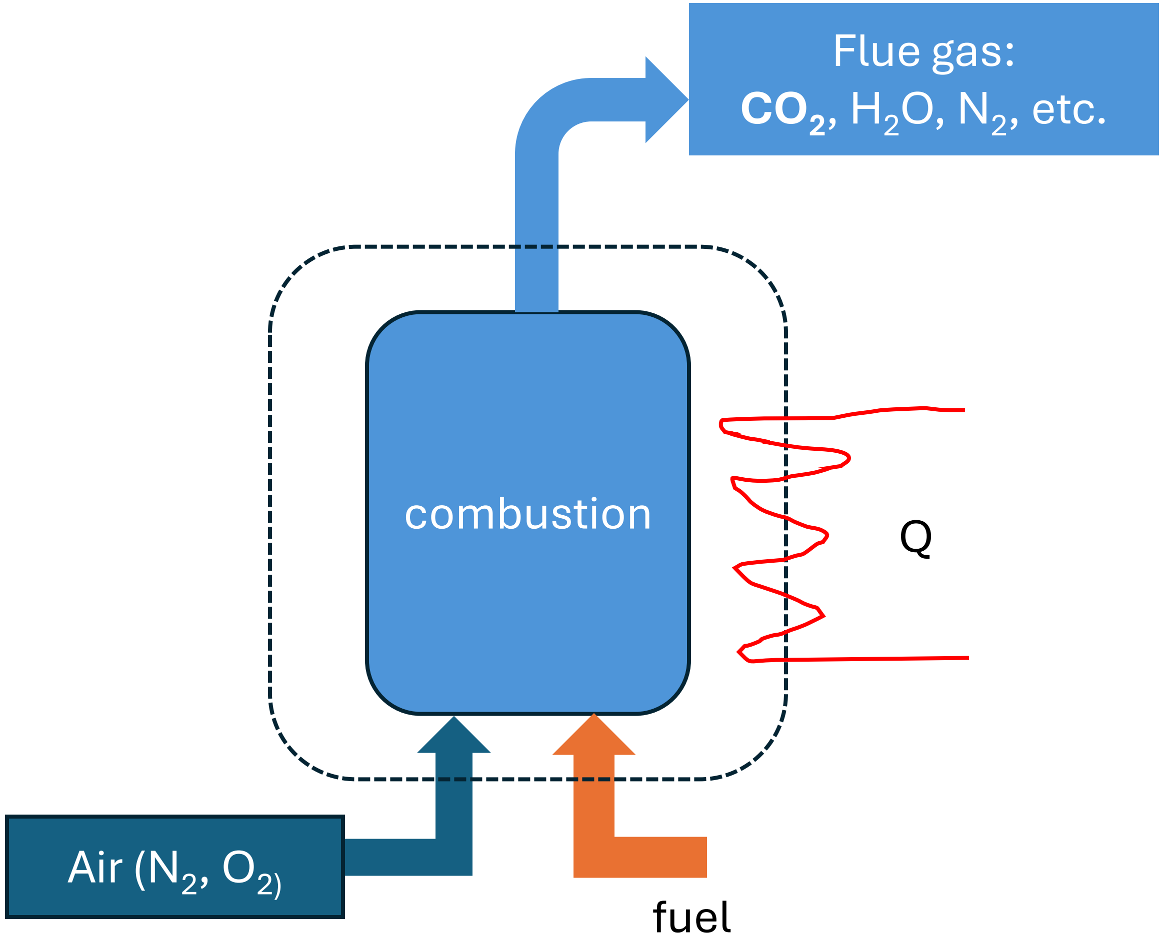
Chemical looping refers to the use of a chemical intermediate in a reaction regeneration cycle to decompose one target reaction into two or more sub-reactions.

The term ‘chemical looping combustion’ was first used by Ishida, Zheng, and Akehata (1987) in the context of an investigation of an unmixed combustion process using metal oxides to selectively transport oxygen from one reactor to another.

It refers to a process in which a solid oxygen carrier material selectively transports oxygen from an air reactor to a fuel reactor with the purpose of fully oxidizing a fuel to CO2 and H2O in the fuel reactor

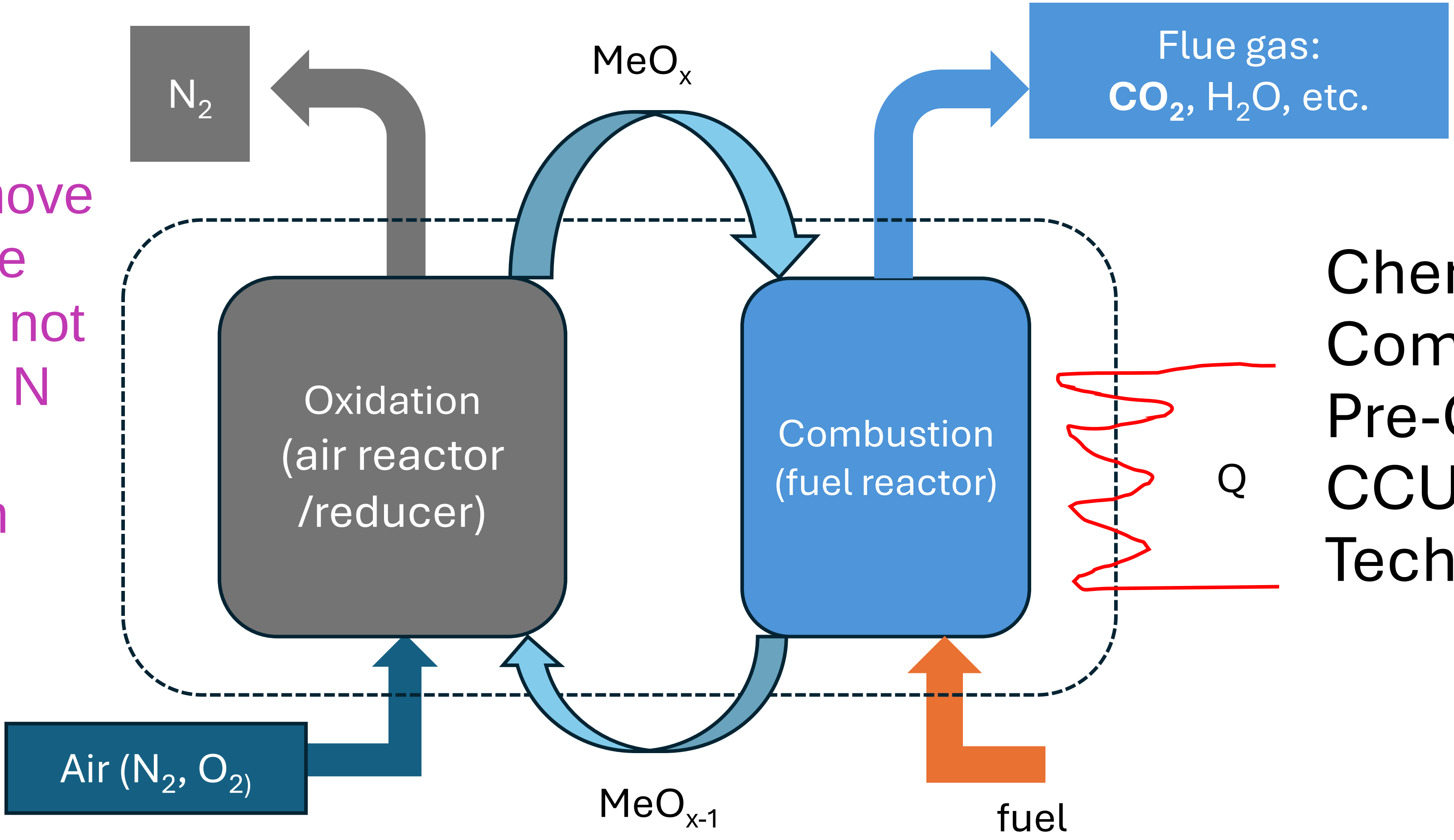
Introduction Chemical Looping

Conventional combustion to produce Heat (Q) resulting in Flue Gas.



Introduction Chemical Looping

tried to remove NO from the flue gas by not introducing N to the combustion



Chemical Looping Combustion is Pre-Combustion CCUS Technologies

Oxidation and Reduction

- **Oxidation is the loss of electrons or increase in oxidation state of a molecule, atom, or ion in a chemical reaction.** Reduction is a gain of electrons or the decrease in the oxidation state of a molecule, atom, or ion. In a redox reaction, one chemical species is reduced, while another is oxidized. Redox stands for **red**uction-**ox**idation.
- Originally oxidation meant adding oxygen to a compound. This is because oxygen gas (O_2) was the first known oxidizing agent. Adding oxygen to a compound typically meets the criteria of electron loss and an increase in the oxidation state, but the definition of oxidation was expanded to include other types of chemical reactions.
- A classic example of oxidation occurs between iron and oxygen in moist air, forming iron oxide or rust. The iron is said to have oxidized into rust. The chemical reaction is:

$$4\ Fe + 3\ O_2 + 6\ H_2O \rightarrow 4\ Fe(OH)_3 \text{ or } 2Fe_2O_3{\cdot}6H_2O$$

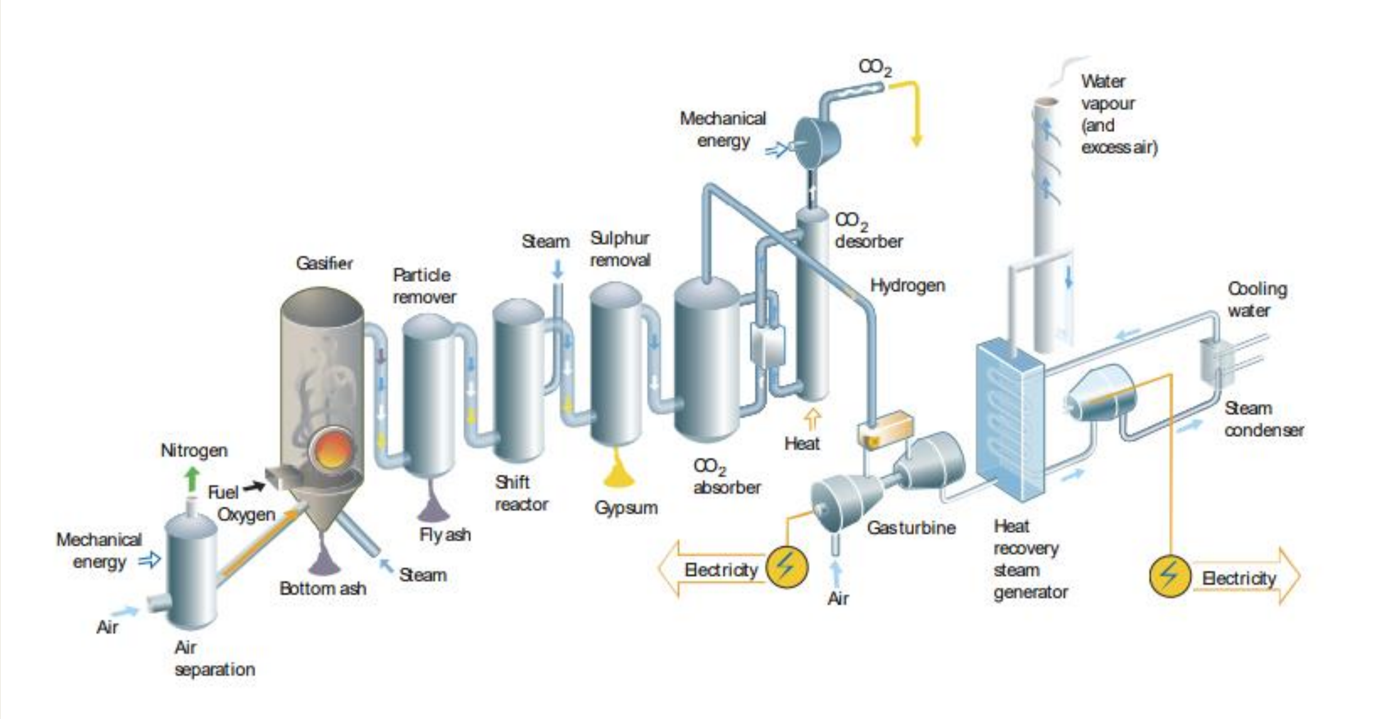
https://sciencenotes.org/what-is-oxidation-definition-and-examples/

Oxidation Number

1. The oxidation number of an atom in a neutral free element is zero. A free element is considered to be any element in an uncombined state, whether monatomic or polyatomic. For example, the oxidation number of each atom in Fe, Li, $\mathrm{N_2}$, Ar, and $\mathrm{P_4}$ is zero.
2. The oxidation number of a monatomic (composed of one atom) ion is the same as the charge of the ion. For example, the oxidation numbers of $\mathrm{K^+}$, $\mathrm{Se^{2-}}$, and $\mathrm{Au^{3+}}$ are $+1$, -2, and $+3$, respectively.
3. The oxidation number of oxygen in most compounds is -2.
4. The oxidation number of hydrogen in most compounds is $+1$.
5. The oxidation number of fluorine in all compounds is -1. Other halogens usually have an oxidation number of -1 in binary compounds, but can have variable oxidation numbers depending on the bonding environment.
6. In a neutral molecule, the sum of the oxidation numbers of all atoms is zero. For example, in $\mathrm{H_2O}$, the oxidation numbers of H and O are $+1$ and -2, respectively. Because there are two hydrogen atoms in the formula, the sum of all the oxidation numbers in $\mathrm{H_2O}$ is $2(+1)+1(-2)=0$.
7. In a polyatomic ion, the sum of the oxidation numbers of all atoms is equal to the overall charge on the ion. For example, in $\mathrm{SO_4^{2-}}$, the oxidation numbers of S and O are $+6$ and -2, respectively. The sum of all oxidation numbers in the sulfate ion would be $1(+6)+4(-2)=-2$, which is the charge of the ion.

https://chem.libretexts.org/Courses/University_of_Kentucky/UK%3A_CHE_103_-_Chemistry_for_Allied_Health_(Soult)/Chapters/Chapter_11%3A_Properties_of_Reactions/11.1%3A_Oxidation_Numbers

Pre-Combustion CO_2 Capture IGCC

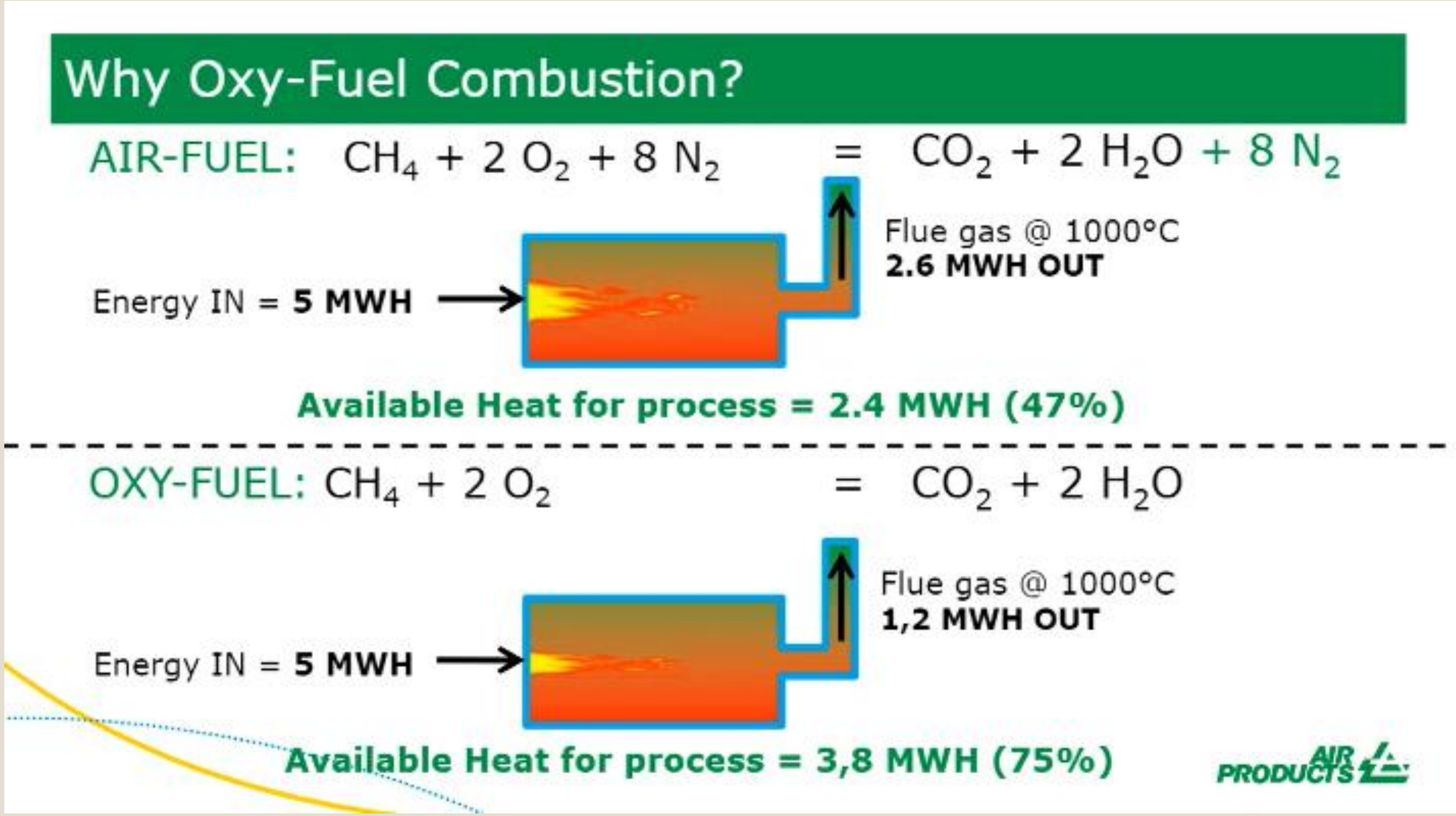


- Typically applied in the context of integrated gasification combined cycle (IGCC) heat and power plants.
- Gasification of solid fuel enables use of high-efficiency combined cycle of a gas turbine and a steam turbine.
- Higher efficiency and lower emissions than coal combustion, but complex gasification technology (OPEX vs. CAPEX).
- Opportunity to capture CO2 at high partial pressure.

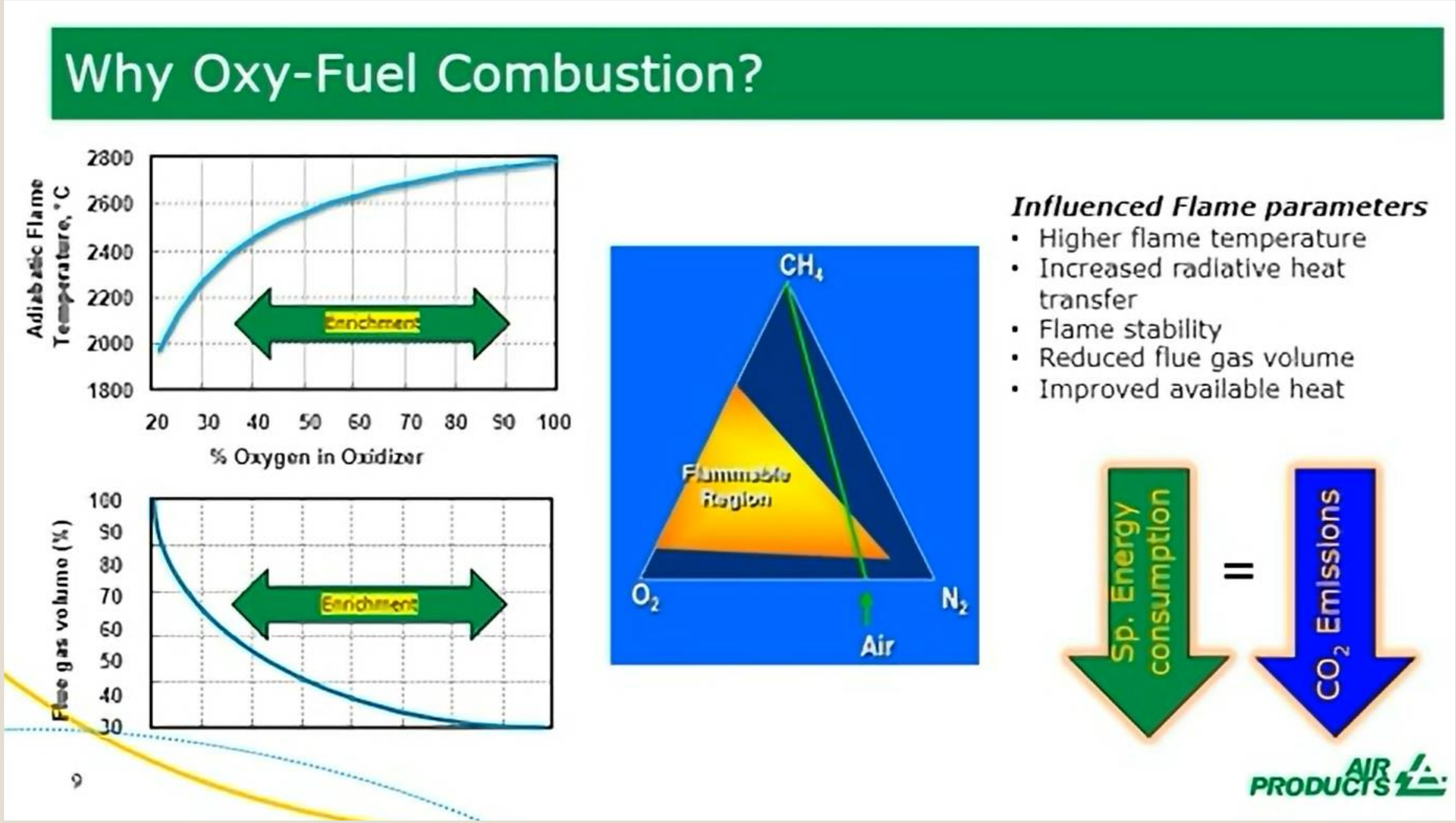
Introduction of Oxy-fuel Combustion

- Motivation on finding a “cleaner” coal option
- Most of today’s combustion applications and operational gas turbines utilize air for combustion process. The use of air as oxidizer generates an exhaust flue gas stream that contains mainly CO_2 , H_2O, O_2, and N_2
- There are three categories of CCS technologies based on capturing CO_2 from a flue gas originating from a thermal power plant, which depends upon the capture process: Pre-combustion, post-combustion, and oxy-combustion/oxy-fuel
- Oxy-combustion follows the idea of burning fuel with medium-purity oxygen (O_2), increasing combustion efficiency and flame temperature compared to air-firing.

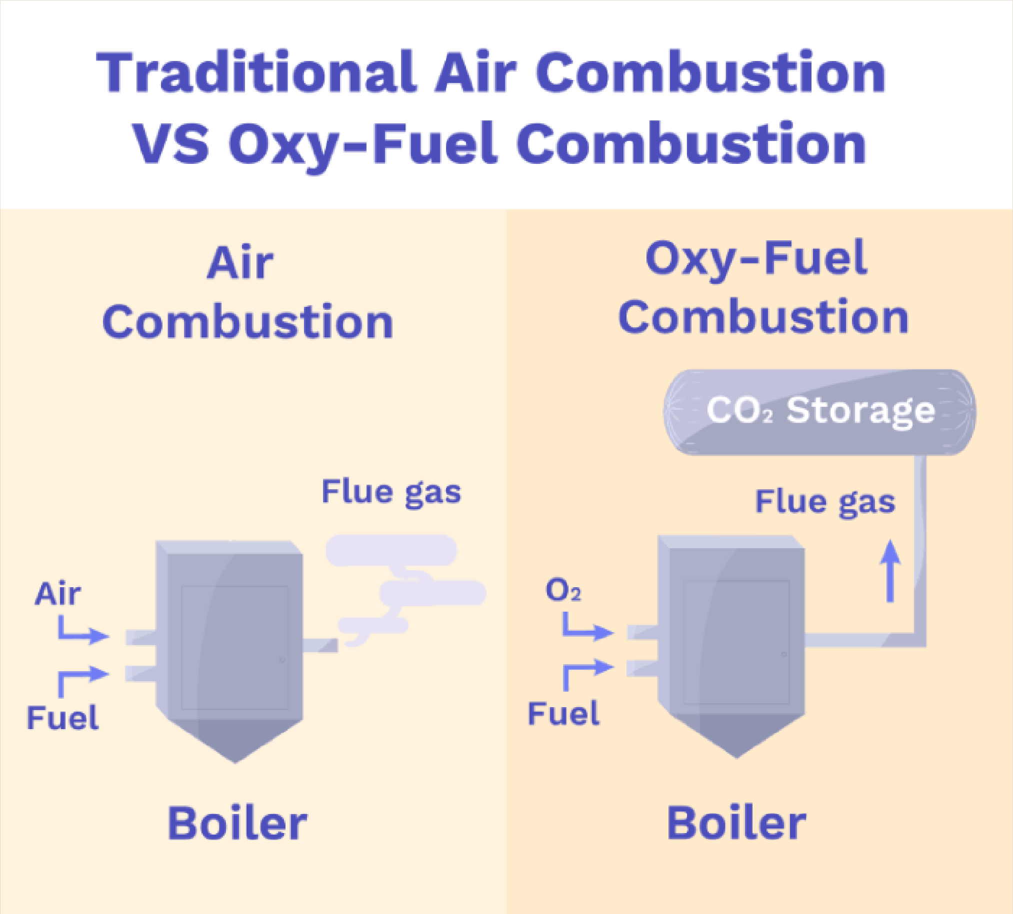
Why Oxyfuel? (1)



Why Oxyfuel? (2)



Introduction: Oxy-fuel Definition



Source: https://climatescience.org/advanced-oxy-fuel-combustion-

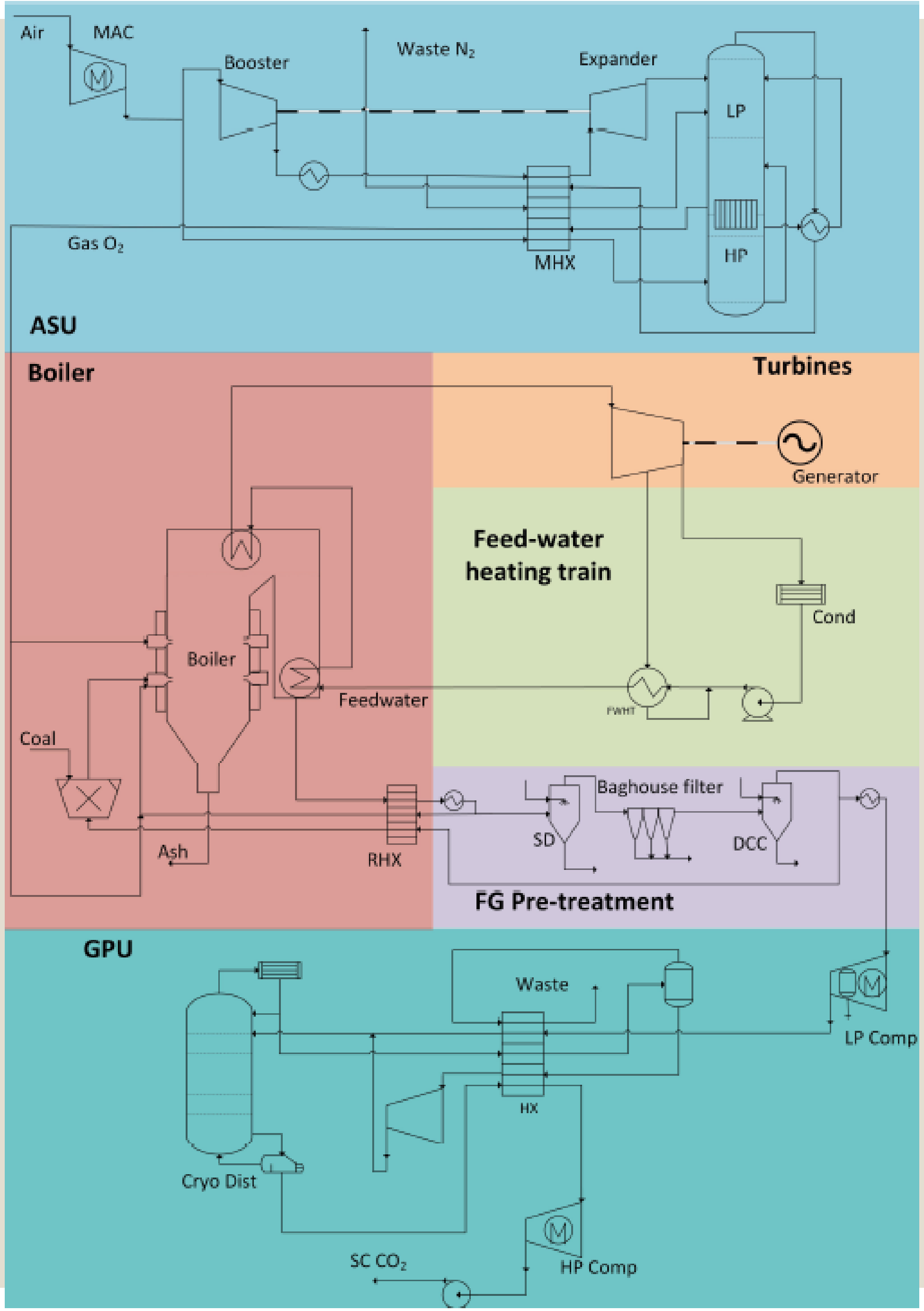
- Oxyfuel is a term used to describe the combustion of carbon-containing fuels with pure oxygen, which achieves a high concentration of carbon dioxide
- Compared to the flue gas of current power plants, which contains concentrations of CO_2 of around 12–15 vol. %, this figure is around 89 vol. % in oxyfuel plants
- After flue gas purification and scrubbing, the flue gas is mainly comprised of a carbon dioxide/steam mixture. By condensing the steam out of the flue gas, a CO_2-rich flue gas is produced, which is then compressed ready for transport to the storage site.

Oxy-Combustion System Overview

1. Air Separation Unit (ASU)
2. Boiler
3. Turbine
4. Pre-treatment Flue gas
5. Gas Processing Unit

Type of ASU:

- Cryogenic Air Separation Units
- Adsorptive Air Separation
- Membrane Technology
- Chemical Production of Oxygen



Post-Combustion Carbon Capture

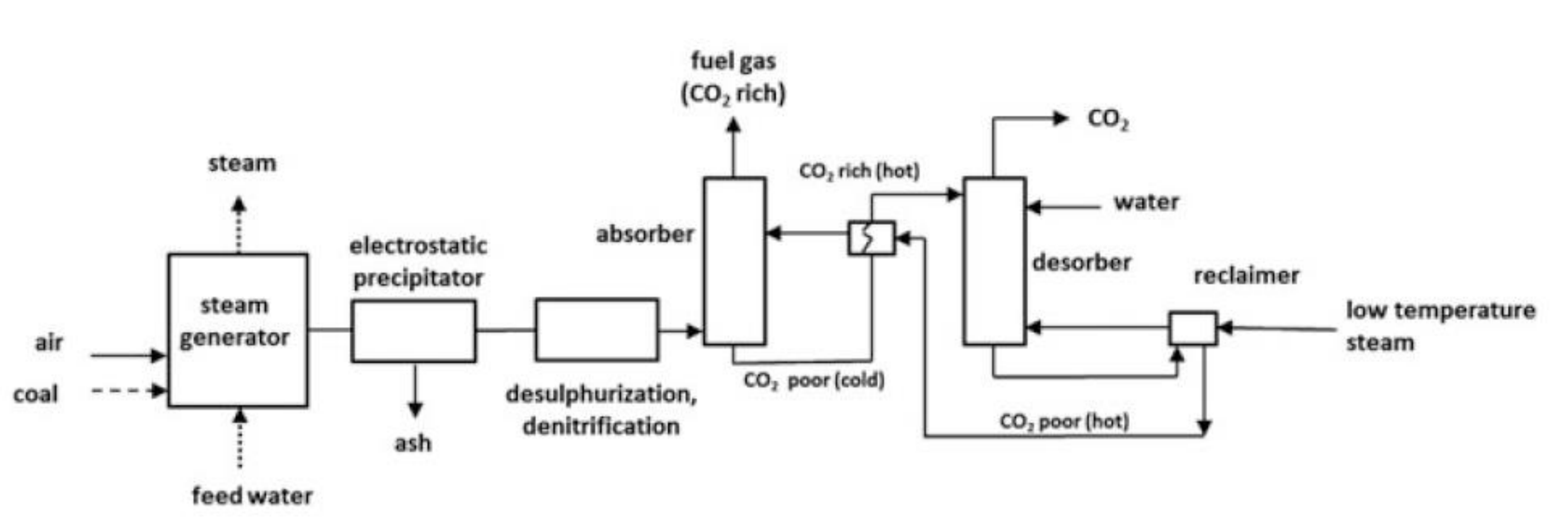
- In post-combustion capture, CO_2 is separated from combustion product gases that are predominantly nitrogen and water, though contaminants such as particulates or sulfur and nitrogen oxides could also be present. Post-combustion capture has been tested at scale for pulverized-coal plants, but could also be applied to natural-gas-fired plants.
- Post-combustion systems extract CO_2 from flue gases generated by burning primary fuel in air.
- These systems typically use a liquid solvent to capture the small amount of CO_2 (usually 3–15% by volume) present in the flue gas, which is mainly composed of nitrogen from the air.

Intergovernmental Panel on Climate Change. Carbon Dioxide Capture and Storage, 2005.

Post-Combustion Carbon Capture

- In modern pulverized coal (PC) power plants or natural gas combined cycle (NGCC) power plants, current post-combustion capture systems generally use an organic solvent like monoethanolamine (MEA).
- Current post-combustion and pre-combustion systems for power plants could capture 85–95% of the CO2 that is produced. Higher capture efficiencies are possible, although separation devices become considerably larger, more energy intensive and more costly.
- Capture and compression need roughly 10–40% more energy than the equivalent plant without capture, depending on the type of system.

Post-combustion CO2 Capture: Amine Scrubbing



TERIMA KASIH