# PC 3 Carbon Capture & Storage

PHY 555 – Energy & Environment

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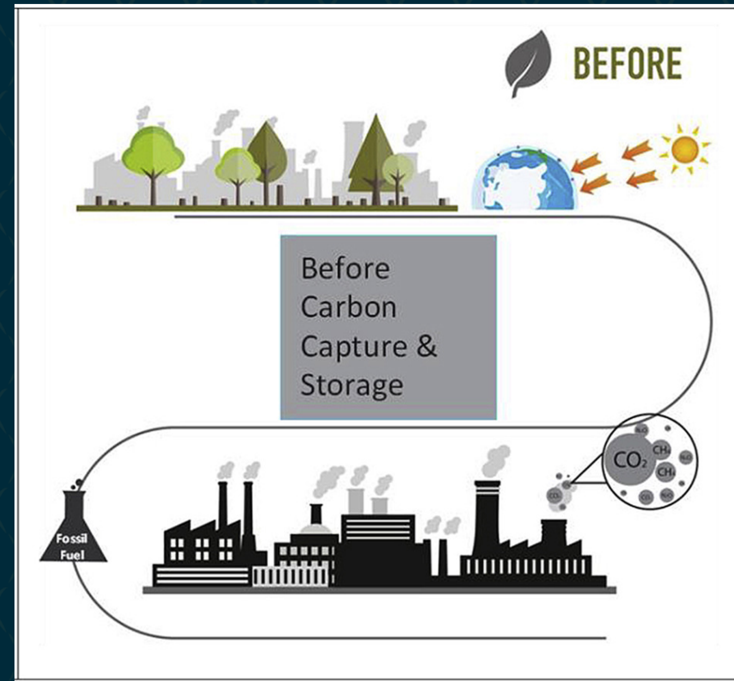


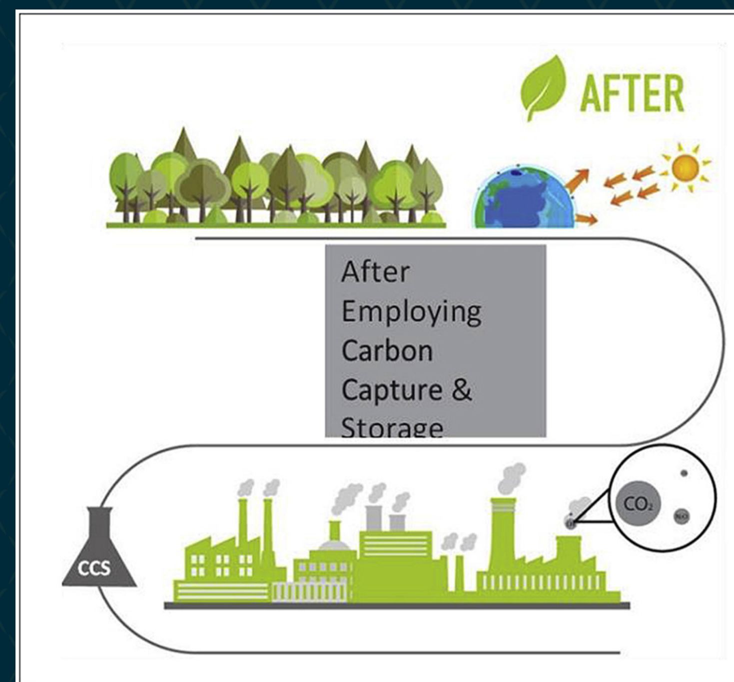


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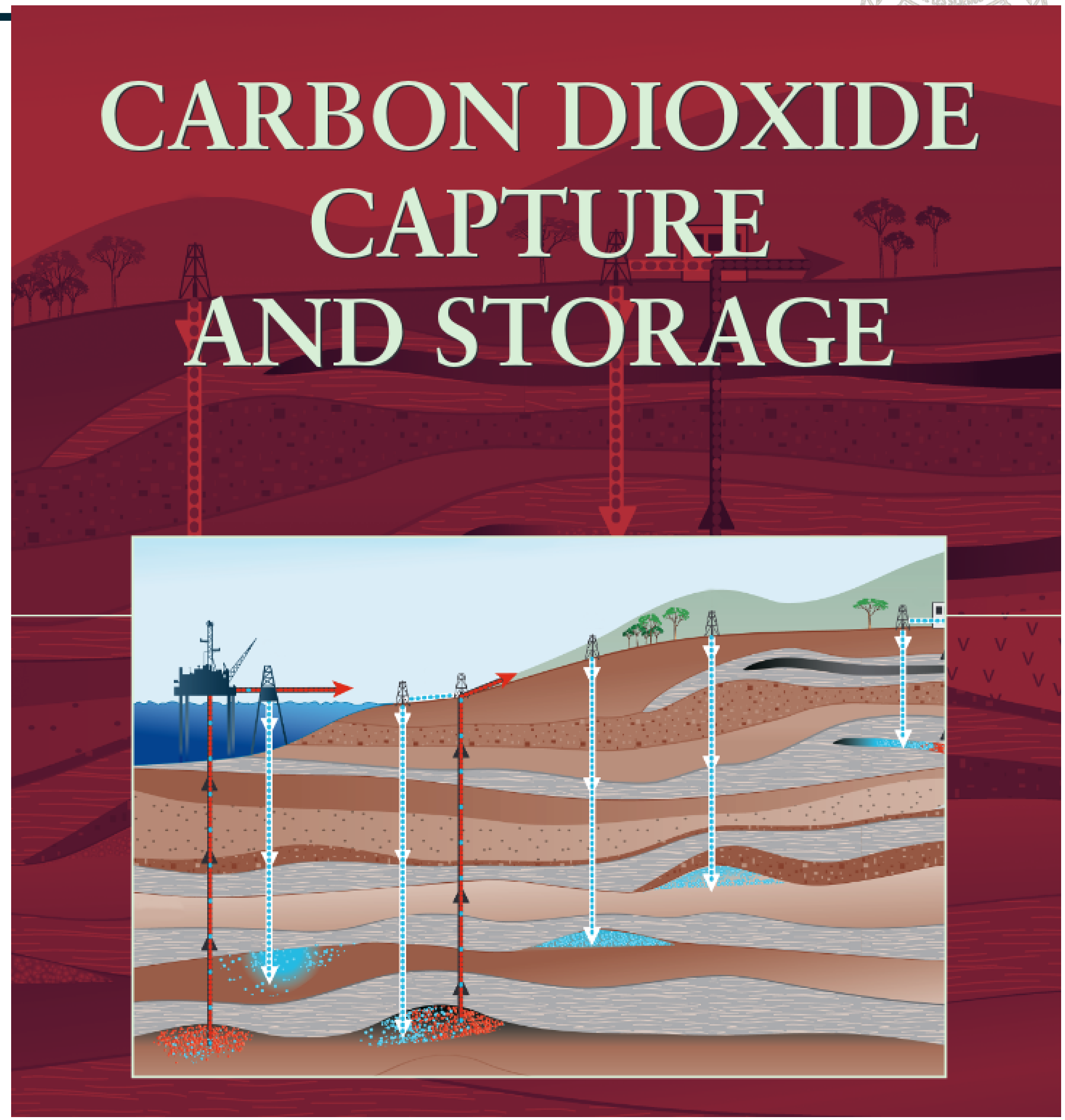
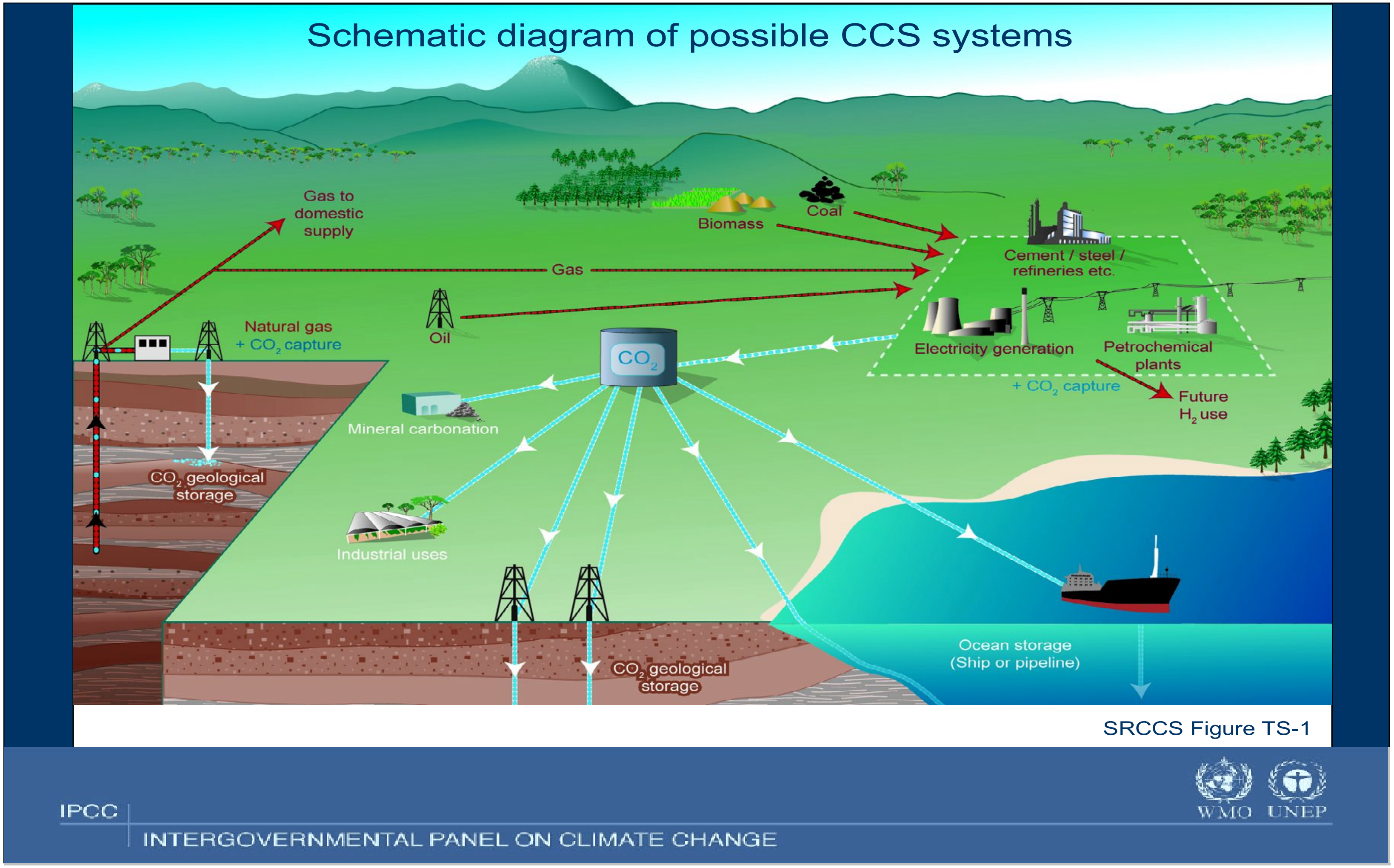
# Why CCS?

- Electricity production will remain massively fuelled by fossil energy
- Some industries (e.g. cement) remain large $CO_2$ emitters

  ⇒ Carbon Dioxide Removal (CRD) or Capture Capture & Storage (CCS) mandatory
- See 2005 Special IPCC report



# CCS - Overview




**Source: IPCC Special Report on Carbon dioxide Capture and Storage**

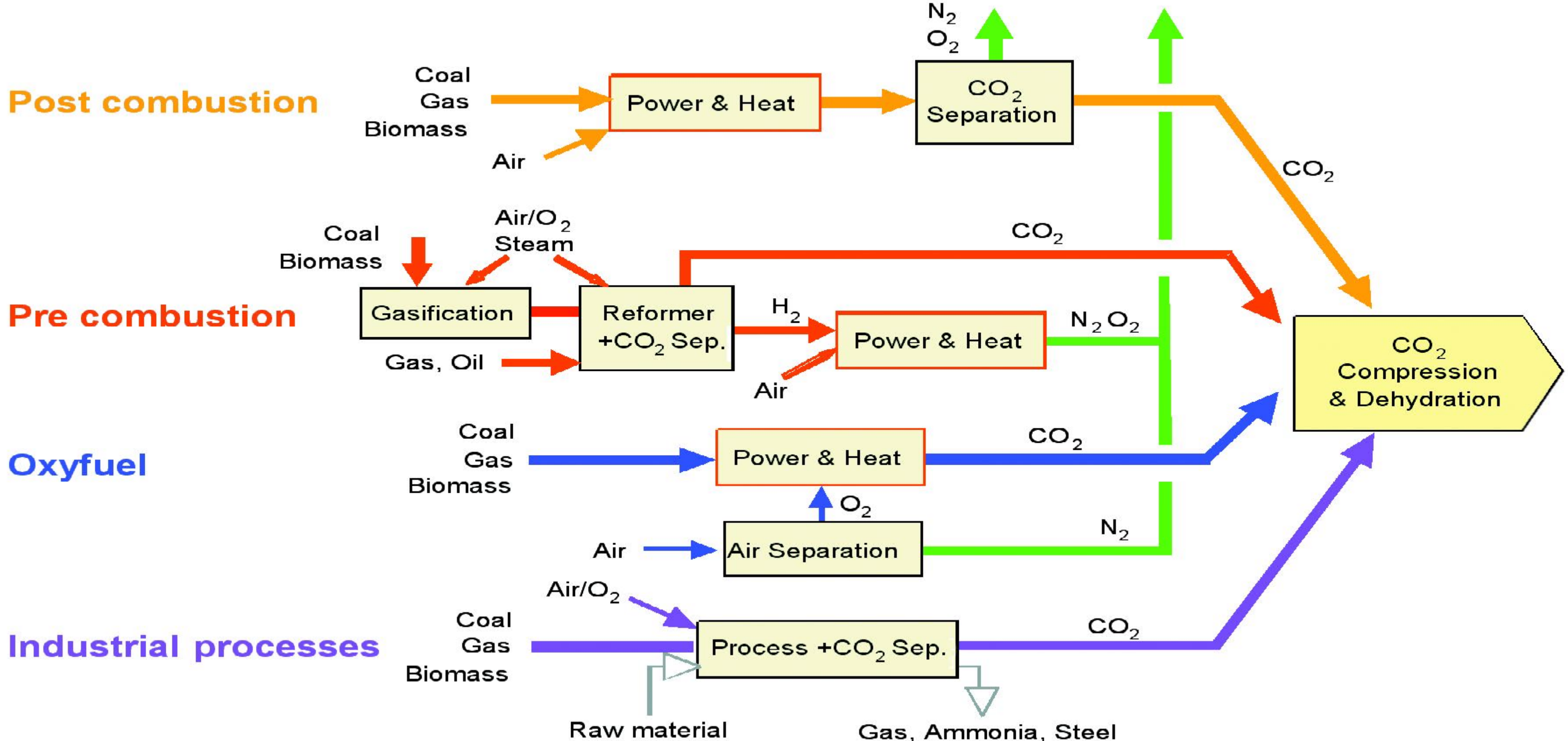
# $CO_2$ Capture and transportation

- Capture: essentially for large installations
  - power plans (gas, coal, IGCC)
  - CO2 neutral biofuel factories
  - chemical industry
  - steel factories
- $CO_2$ Transportation options
  - gas pipelines (supercritical $CO_2$)
  - supertanker (liquid, refrigerated $CO_2$)

# Storage options

- geological:
  - depleted deposits (oil, gas)
  - underground cavities
  - saline aquifers
- oceanic (not considered any more):
  - dissolution in seawater
  - formation of $CO_2$ lakes at the bottom of the sea
- mineralization : carbonates
- valuation:
  - chemical production of methanol, urea
  - methane extraction (coal seams)
  - enhanced oil recovery
  - biomass production (algae)

# Synoptic




Source: IPCC Special Report on Carbon dioxide Capture and Storage

# $CO_2$ Capture – Overview

- post-combustion : extract $CO_2$ from exhaust
  - Retrofit of existing plans
  - Reduced yield (energetic cost of separation due to low concentration)
  - corrosive and / or toxic chemicals, sensitive to pollutants
- pre-combustion : gasification of coal, biomass, garbage
  - associated production of hydrogen (syngaz)
  - only for combined cycle power plants (IGCC)
  - requires air separation (ASU)
  - gas turbines need to be adapted
- oxy-combustion : burning coal in $O_2$ / $CO_2$
  - very high concentration CO2 (85-99%) in exhaust gas
  - requires air fractionation: liquefaction / "rectification", pressure-swing-absorption (PSA), membranes

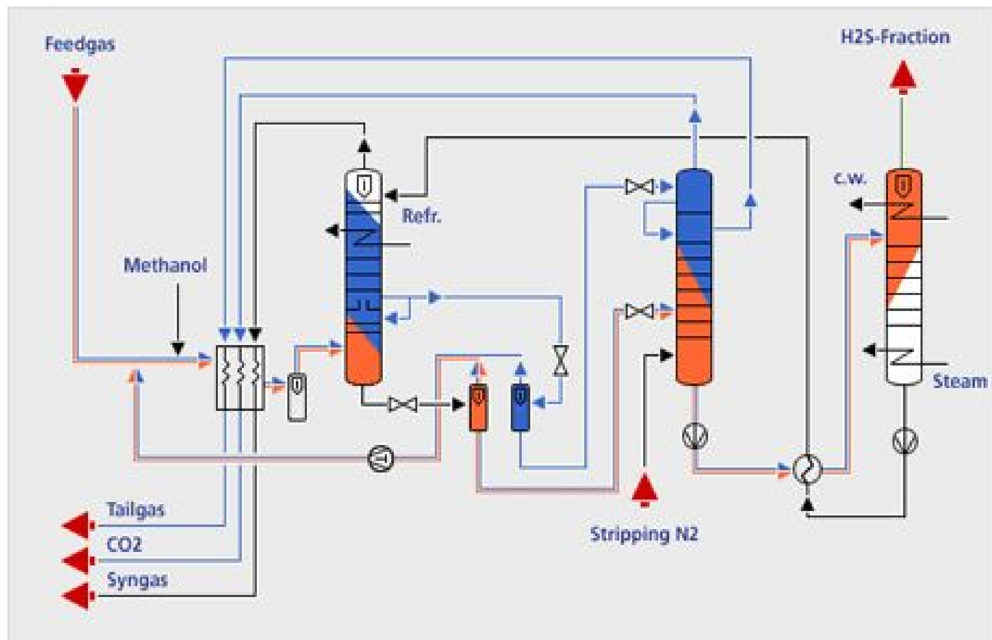
# Gibbs Energy

- Spontaneous evolution of a system is governed by the minimum of a state function (extensive)
  - Isolated system: S
  - Monothermal isochoric system: $F = U - TS$
  - Monobar monothermal system: $G = U + PV - TS$

- Role of Gibbs Energy:
  - At low temperature, G is dominated by H: a reaction takes place spontaneously if it is exothermic (H )
  - At high temperature, G is dominated by S: a reaction takes place spontaneously if it increases disorder (e.g. vaporization at T> 100° C)
  - Existence of equilibrium temperature (e.g. boiling water)

# Post-combustion: physical absorption

- applied on an industrial scale
  - cleaning of natural gas or LPG
  - syngaz cleaning (chemical industry, $NH_3$ production)
- physical process, efficiency = f (pressure, concentration)
  - dissolution of $CO_2$ (or $H_2S$, HCN, COS, ...) at high pressure
  - low pressure gas release
- several processes on the market

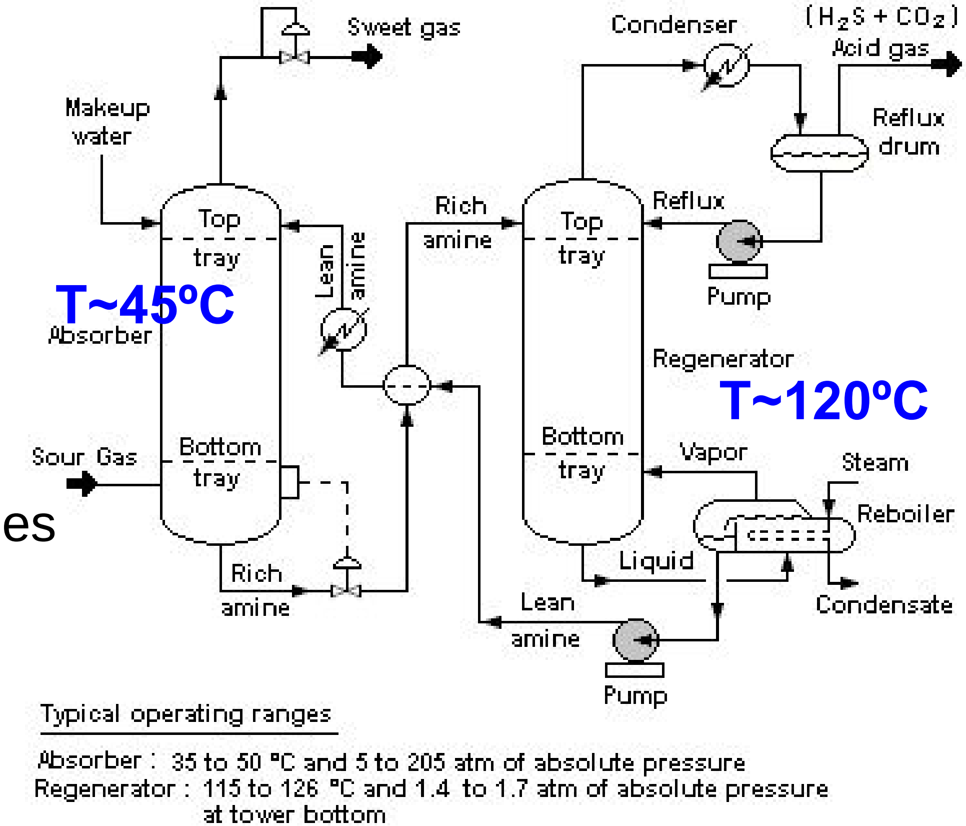


# Post-combustion: chemical absorption

- absorption-neutralization (scrubbing)
  - "Softening" of acid gases,
  - desulfurization
  - refining of natural gas ($CH_4$ / $CO_2$ mixture)
- chemical processes:
  - neutralization with light organic bases
    - MEA (mono-ethanolamine)
    - DEA (diethanolamine)
    - MDEA (methyldiethanolamine)
  - Absorption: 35–50 ºC 5–200 bar
  - Regeneration: 115–126 ºC 1–2 bar
- Alternative: Carbonate Looping (lime loop)
  - absorption (carbonation) : $CaO + CO2 \rightarrow CaCO3$ 650–850ºC
  - regeneration (calcination) : $CaCO3 \rightarrow CaO + CO2$ 900-1100ºC

T~45ºC

T~120ºC



# Pre-combustion: gasification

- Goal: exhaust without $CO_2$
- coal gasification (19th century technology)
  - "syngaz" reaction : $C + H_2O \rightarrow CO + H_2$ $\Delta H = +131{,}3$ kJ/mol
  - incomplete combustion: $C + ½O_2 \rightarrow CO$ $\Delta H = -110{,}5$ kJ/mol
  - balance: $4\,C + O_2 + 2\,H_2O \rightarrow 4\,CO + 2\,H_2$
- Hydrogen production
  - water-gas shift-reaction:

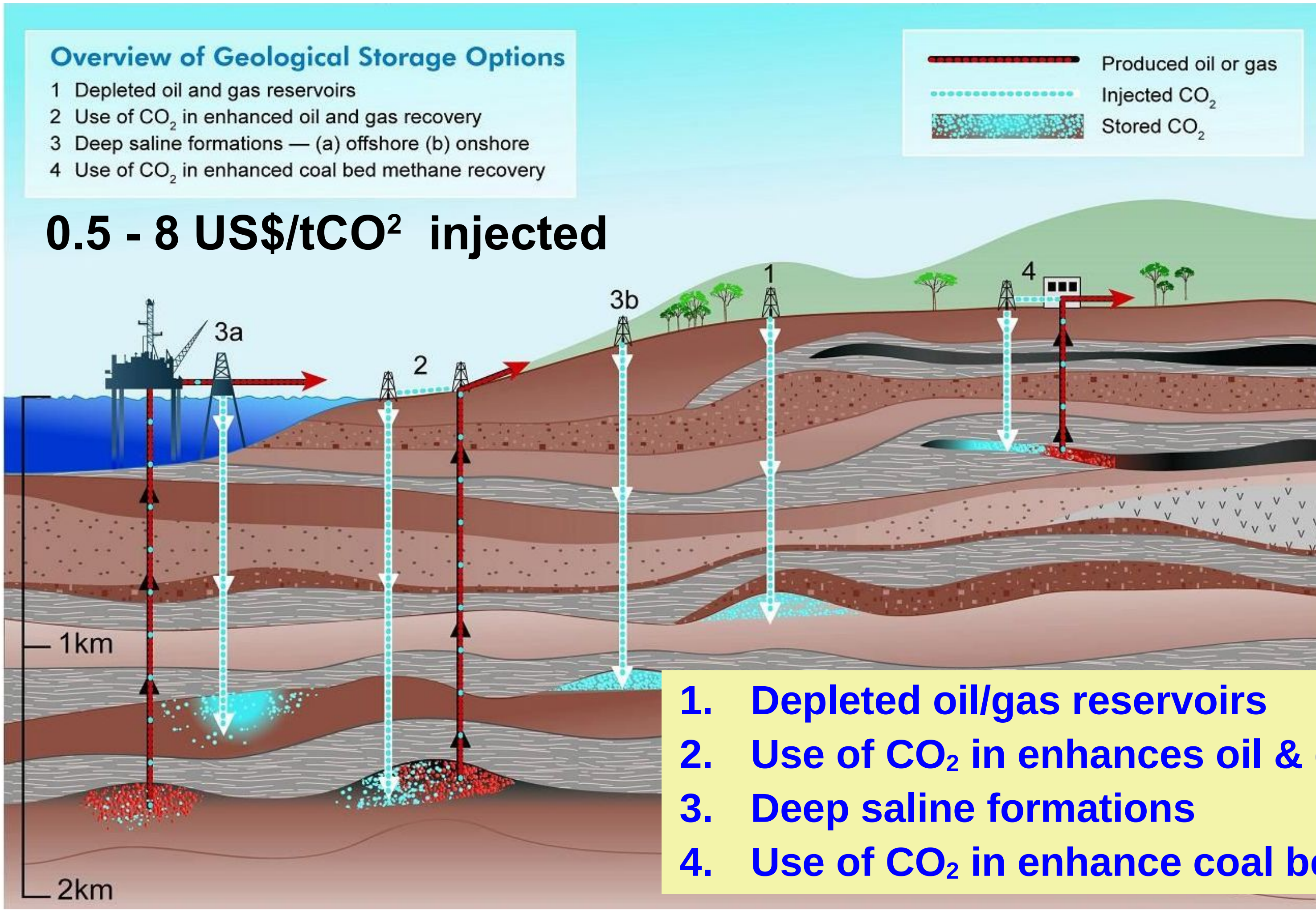
    $CO + H_2O \leftrightarrow CO_2 + H_2$ $\Delta H = -41{,}2$ kJ/mol
  - exhaust gas: $CO_2 + H_2$ (+ $N_2$)
  - $CO_2$ separation as in post-combustion
  - gasification + CCS as a gateway to hydrogen
- Can use a large variety of fuel: biomass, waste, ...

# Capture & Storage : overall cost

| CCS component | Cost range |
|---|---|
| Capture from a power plant | 15 - 75 US$/tCO2 net captured |
| Capture from gas processing or ammonia production | 5 - 55 US$/tCO2 net captured |
| Capture from other industrial sources | 25 - 115 US$/tCO2 net captured |
| Transportation | 1 - 8 US$/tCO2 transported per 250km |
| Geological storage | 0.5 - 8 US$/tCO2 injected |
| Ocean storage | 5 - 30 US$/tCO2 injected |
| | |

**Source: IPCC Special Report on Carbon dioxide Capture and Storage**

# Geological storage: overview



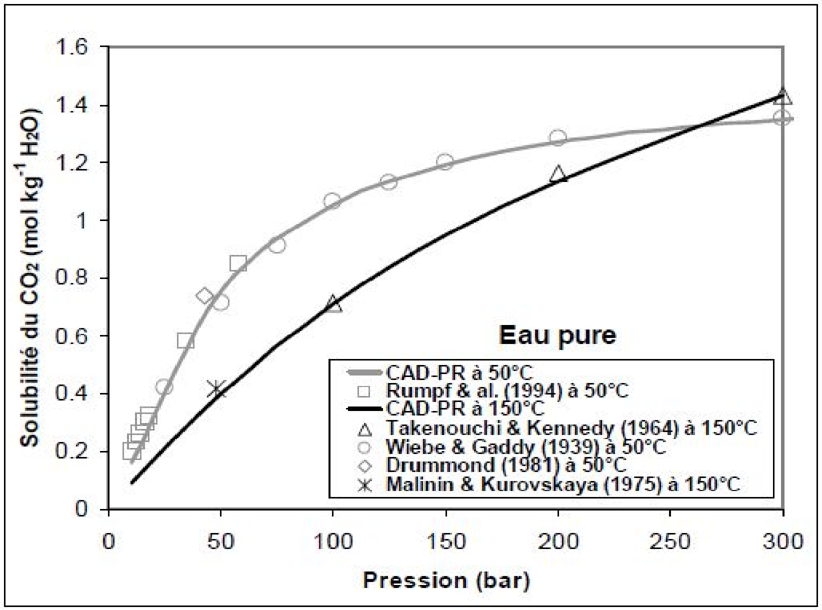

**0.5 - 8 US\$/t$CO^2$ injected**

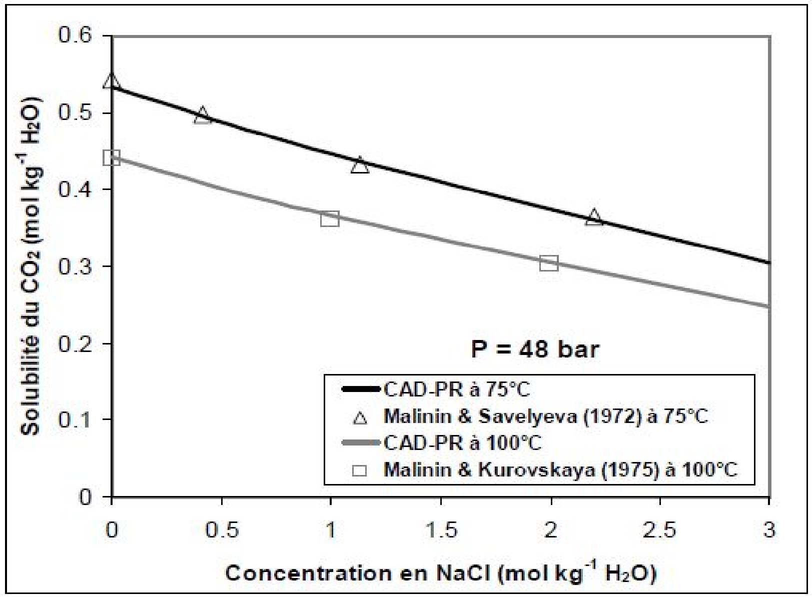
1. **Depleted oil/gas reservoirs**
2. **Use of $CO_2$ in enhances oil & gas recovery**
3. **Deep saline formations**
4. **Use of $CO_2$ in enhance coal bed methane recovery**

**Source: IPCC Special Report on Carbon dioxide Capture and Storage**

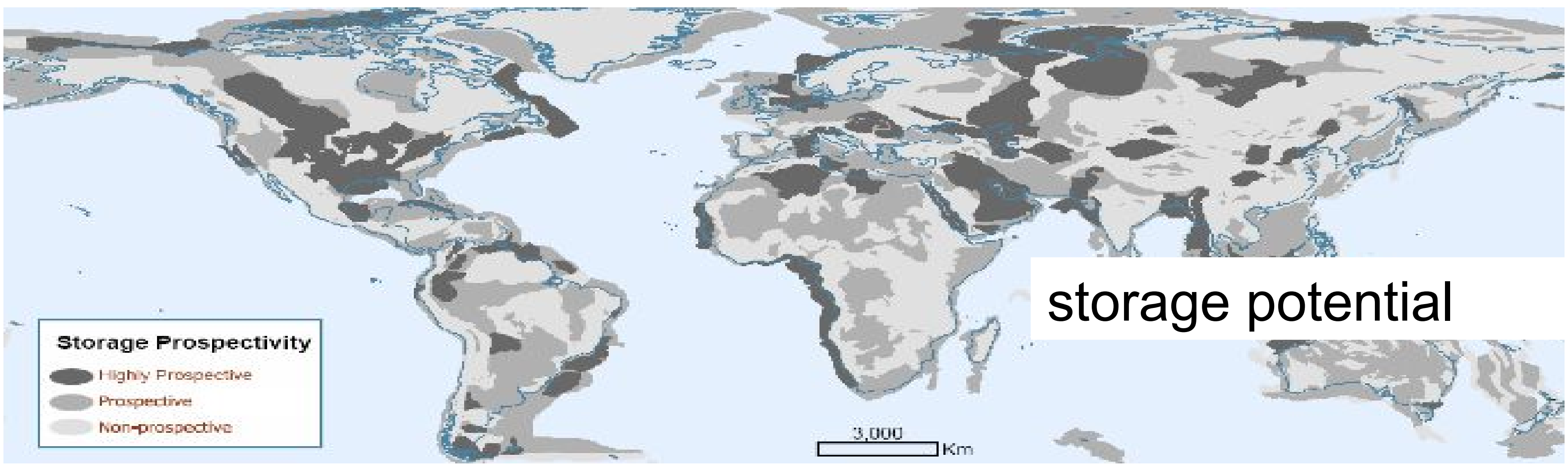
# Deep saline formations

- avoid the gas or supercritical phase (risk of leakage)
  → water dissolution
- avoid contaminating drinking water reservoirs
  → use of saline aquifers (brines)
- solubility of CO2 = f (pressure) (pure water), f (salt concentration)



# Geological storage potential


**Source: Bradshaw & Dance, 2004**

# Candidate Gas Streams

**Table 2.1** Properties of candidate gas streams that can be inputted to a capture process (Sources: Campbell et al., 2000; Gielen and Moriguchi, 2003; Foster Wheeler, 1998; IEA GHG, 1999; IEA GHG, 2002a).

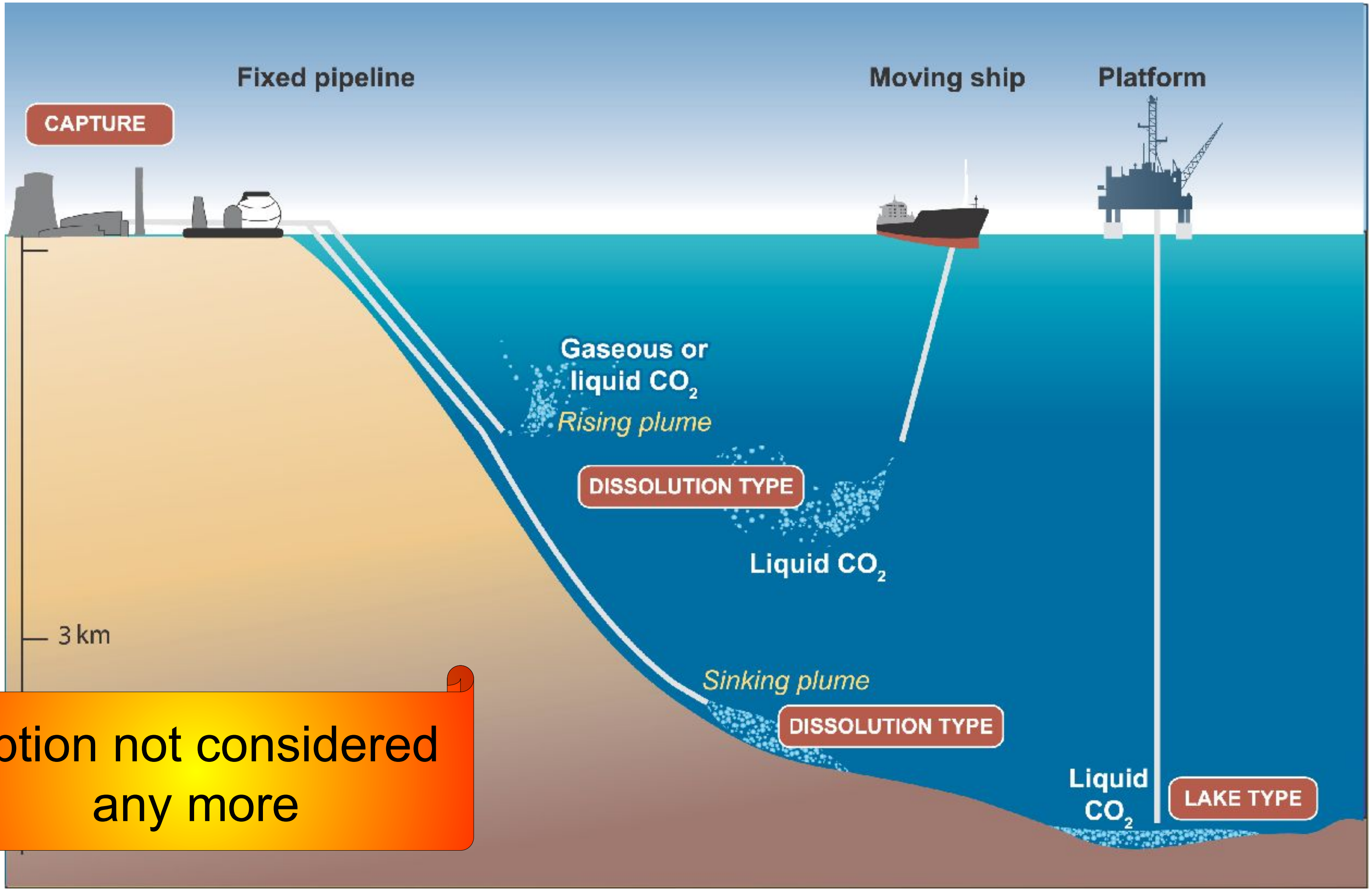
| Source | $CO_2$ concentration % vol (dry) | Pressure of gas stream MPa[a] | $CO_2$ partial pressure MPa |
|---|---|---|---|
| **$CO_2$ from fuel combustion** | | | |
| • Power station flue gas: | | | |
| Natural gas fired boilers | 7 - 10 | 0.1 | 0.007 - 0.010 |
| Gas turbines | 3 - 4 | 0.1 | 0.003 - 0.004 |
| Oil fired boilers | 11 - 13 | 0.1 | 0.011 - 0.013 |
| Coal fired boilers | 12 - 14 | 0.1 | 0.012 - 0.014 |
| IGCC[b]: after combustion | 12 - 14 | 0.1 | 0.012 - 0.014 |
| • Oil refinery and petrochemical plant fired heaters | 8 | 0.1 | 0.008 |
| **$CO_2$ from chemical transformations + fuel combustion** | | | |
| • Blast furnace gas: | | | |
| Before combustion[c] | 20 | 0.2 - 0.3 | 0.040 - 0.060 |
| After combustion | 27 | 0.1 | 0.027 |
| • Cement kiln off-gas | 14 - 33 | 0.1 | 0.014 - 0.033 |
| **$CO_2$ from chemical transformations before combustion** | | | |
| • IGCC: synthesis gas after gasification | 8 - 20 | 2 - 7 | 0.16 - 1.4 |

[a] 0.1 MPa = 1 bar.

[b] IGCC: Integrated gasification combined cycle.

[c] Blast furnace gas also contains significant amounts of carbon monoxide that could be converted to $CO_2$ using the so-called shift reaction.

# Ocean storage: Overview



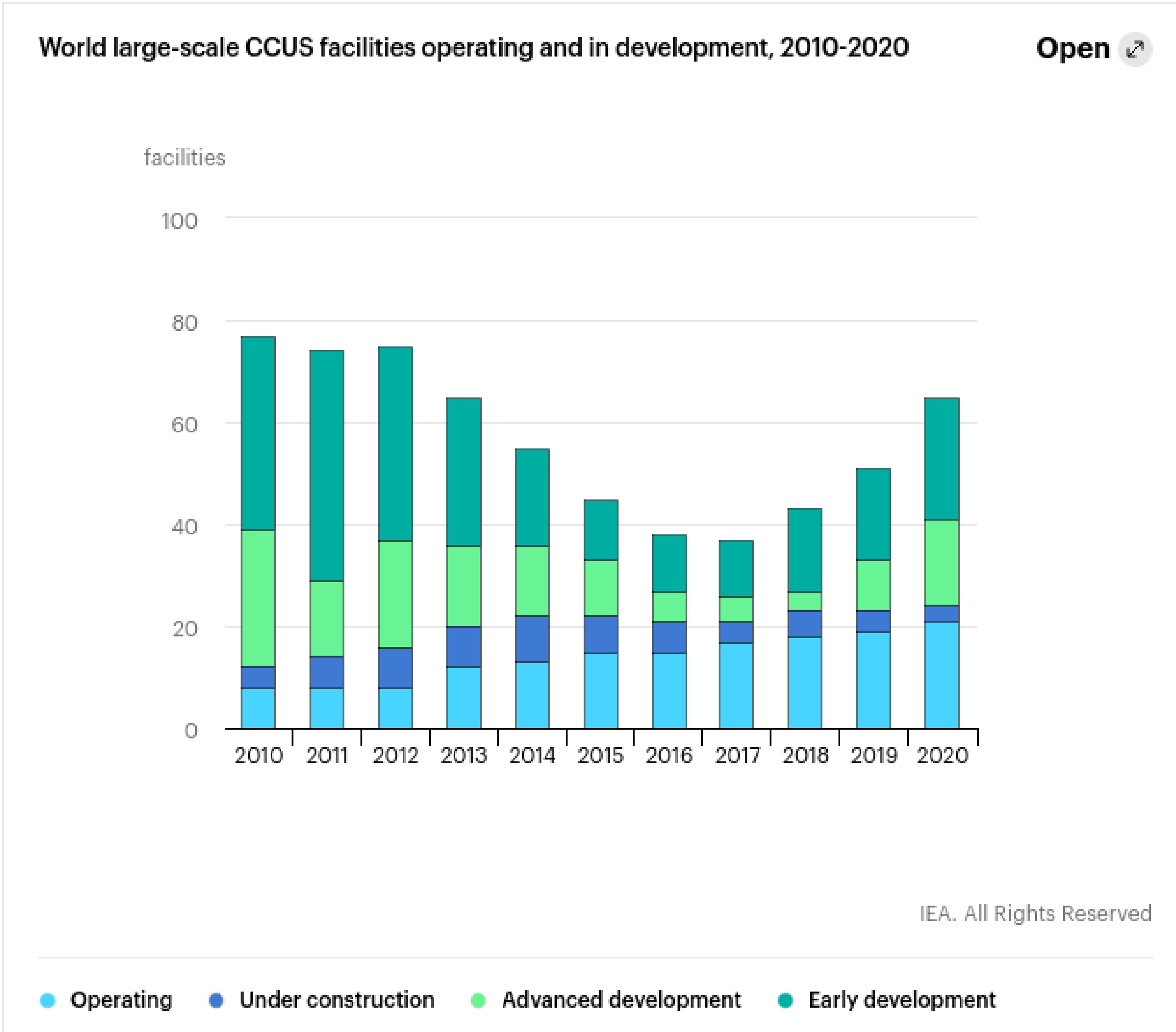

Option not considered any more

**Source: IPCC Special Report on Carbon dioxide Capture and Storage**

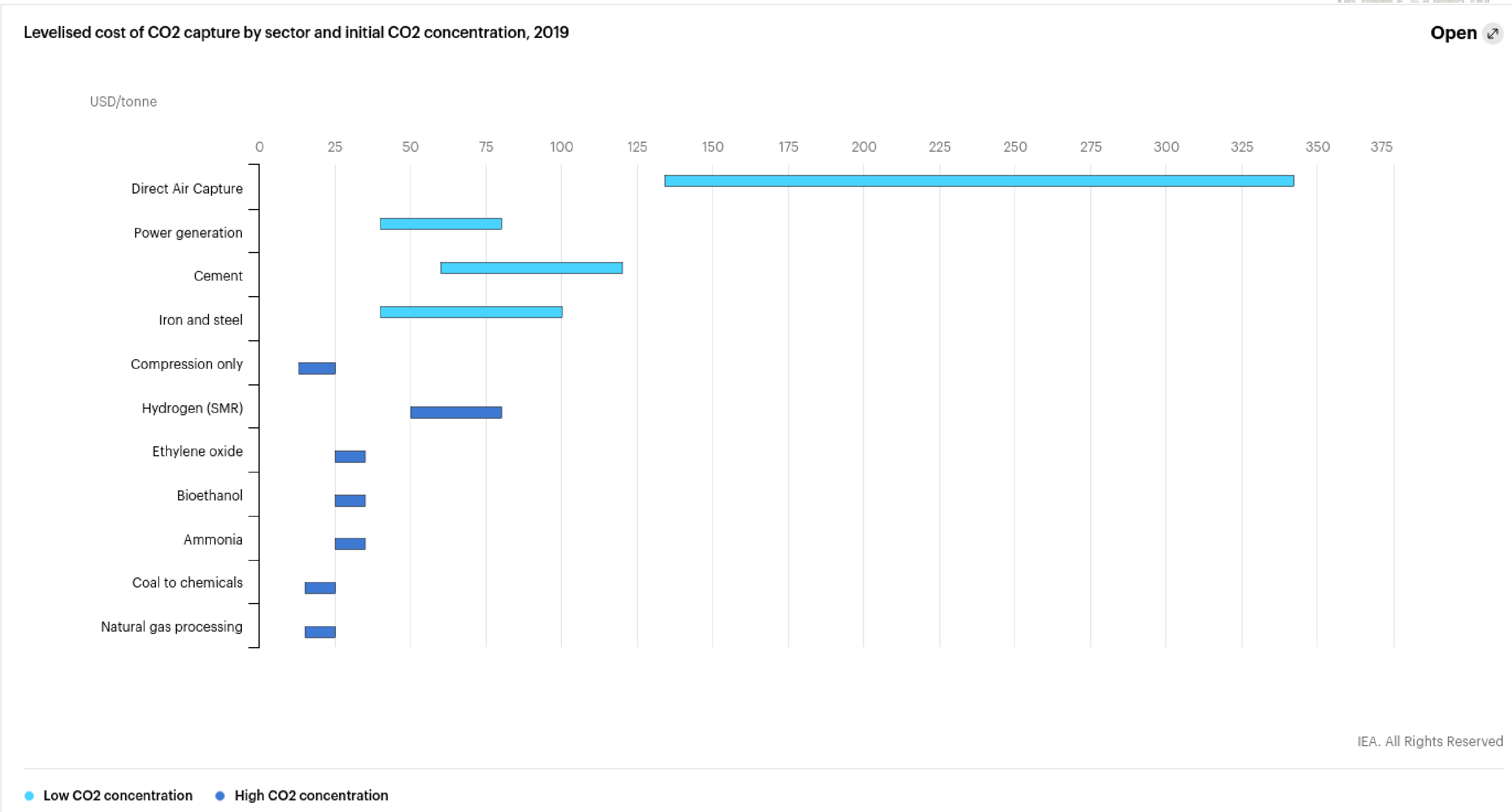
# Lake Nyos

- Lake in Cameroon, 210 m deep, in a volcanic area
- 300 million $m^3$ of liquid $CO_2$ at the bottom of the lake (stratified lake)
- Sudden release on August 21, 1986 following the fall of a section of cliff: "Limnic eruption"
- 1786 dead up to a distance of 30km ...
- Since then: “Nyos organs” remove $CO_2$ (auto-siphon), jet at 50m

# Rise of CCS interest



# Levelized Cost



# Levelized Cost