EG5066 Energy Technologies: Current Issues and Future Directions

Carbon Capture and Storage

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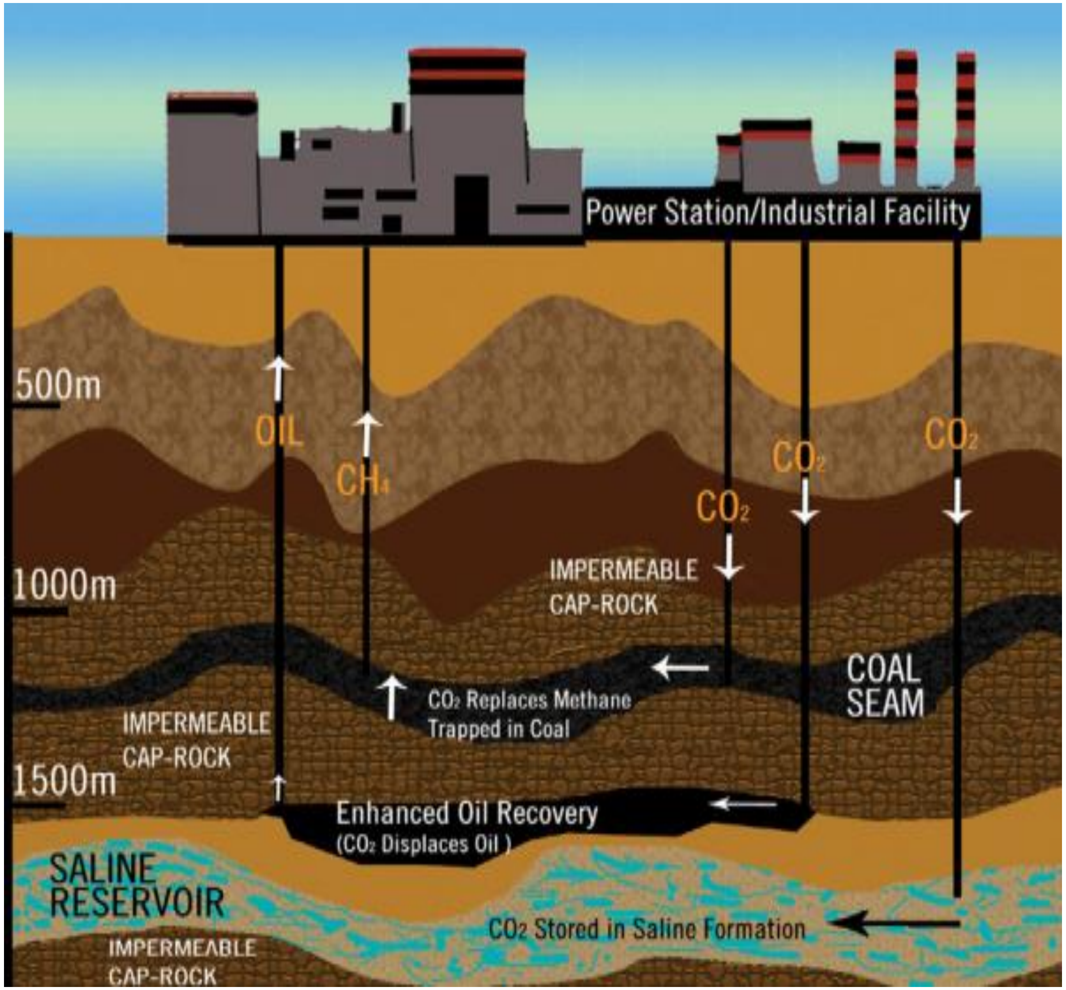
November 2013

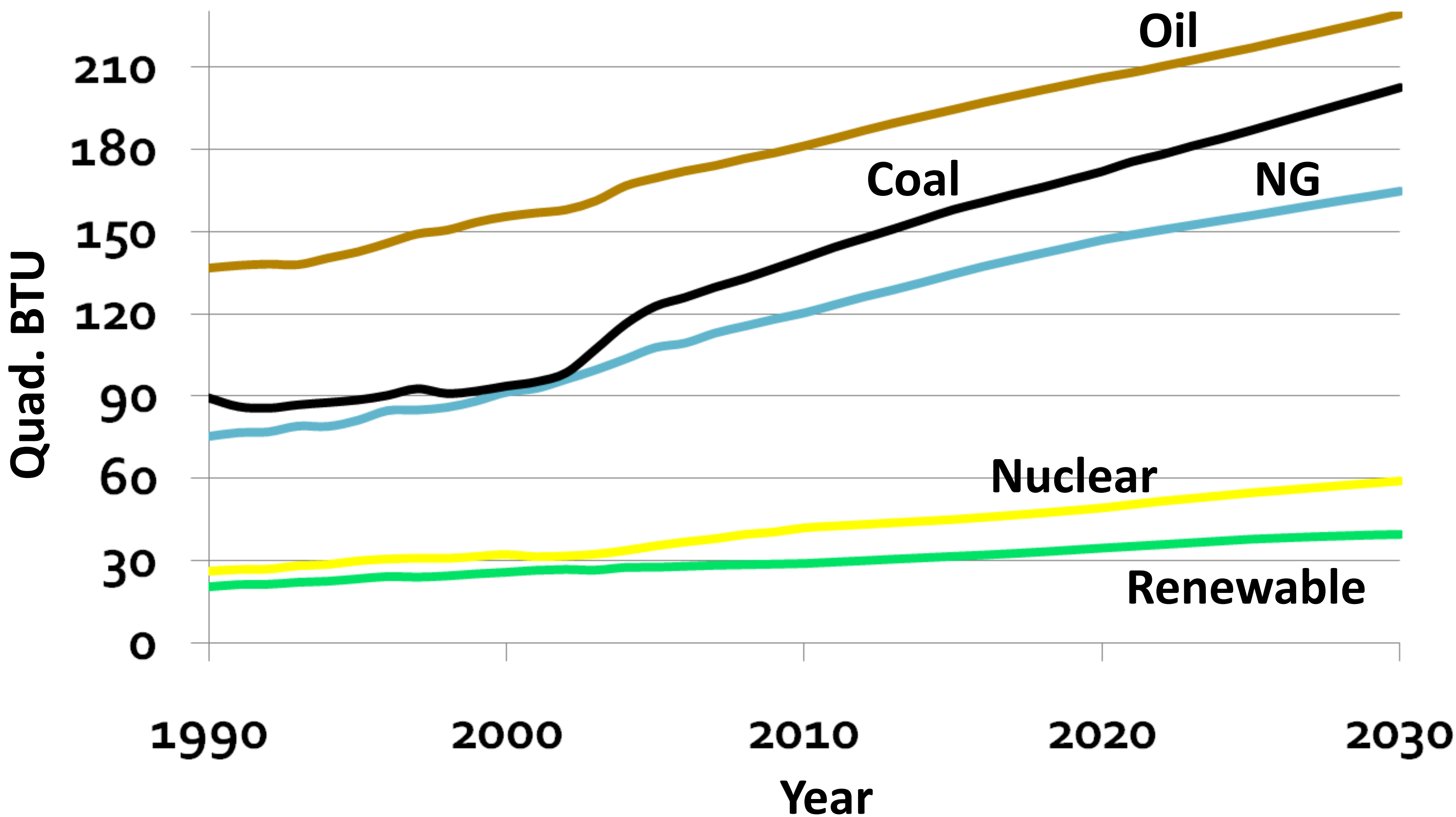
Outline



- Energy Consumption
- Why CCS
- Capture Technologies
- Transport Technologies
- Storage Technologies
- Risks of Geological Storages

Motivation

Energy Consumption



Quad BTU = 10^{15} BTU = 33.434 GW-years

Source: IEA (2011)

Industrial CO_2 Emission Projections

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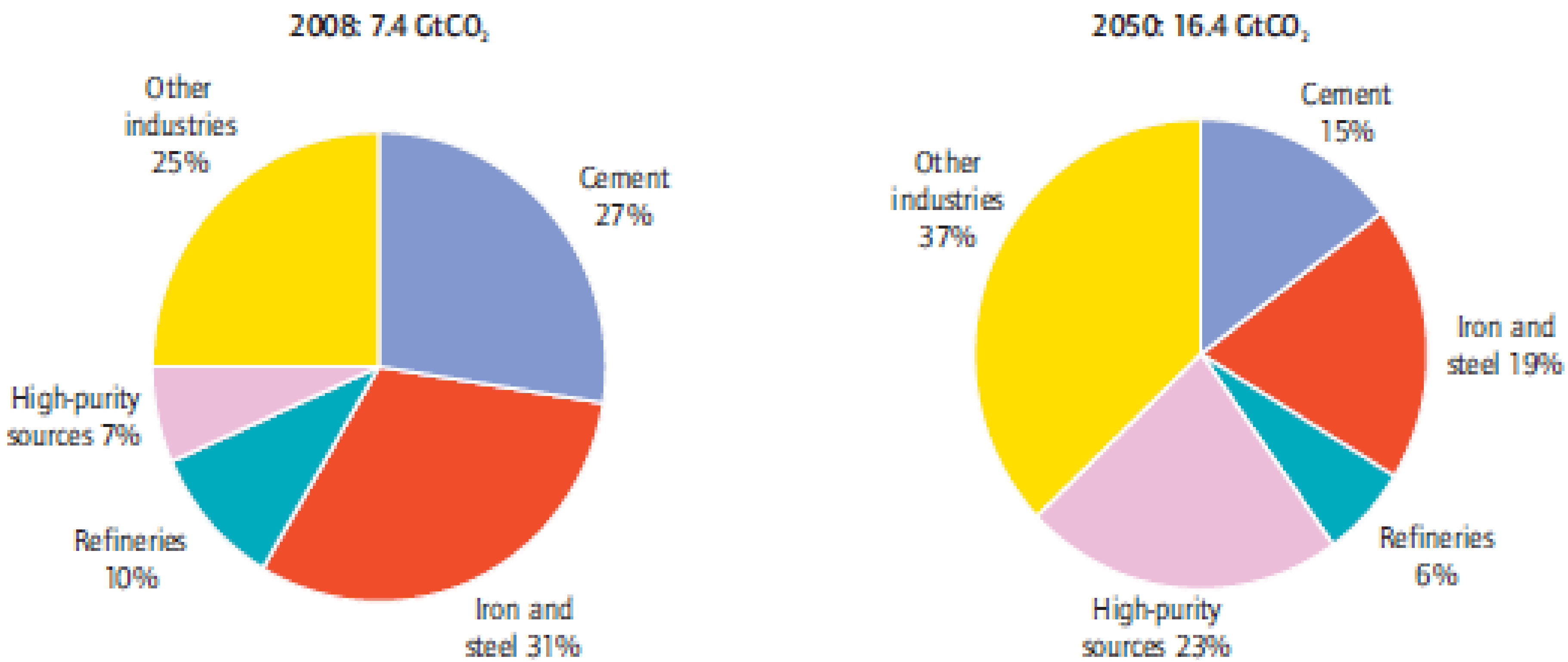
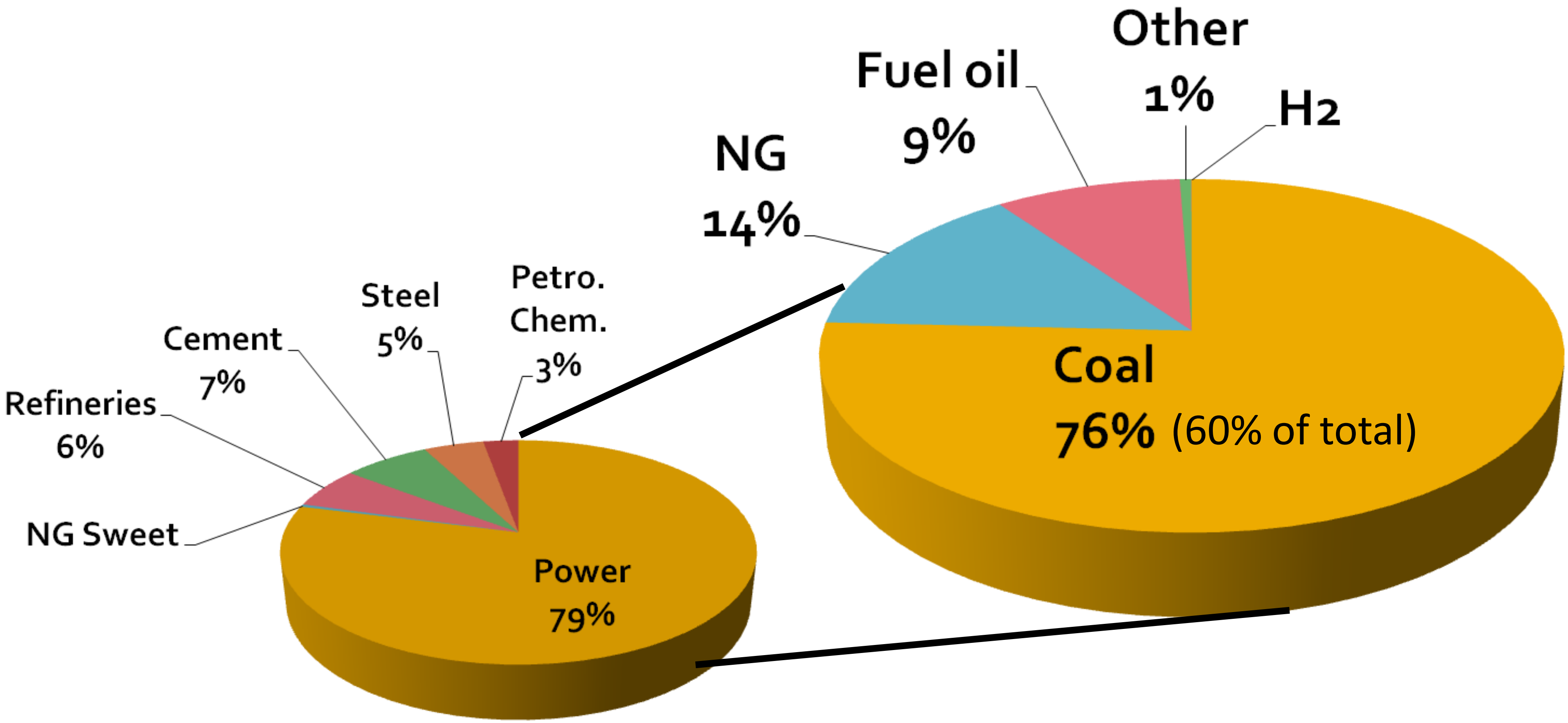


- Global Primary:
  - Energy supply: 12267 million tonnes of oil equivalent (Mtoe) with,
  - CO_2 emissions: 29 Gt
- Total industry and fuel transformation:
  - Energy supply: 4254 Mtoe
  - CO_2 emissions: 7.4 Gt
- **And …**

Source: IEA (2011)

Industrial CO_2 Emissions from Electricity



- **2006: Total 10.5 Mtoe or 79% of all emissions are from power plants to generate electricity.**

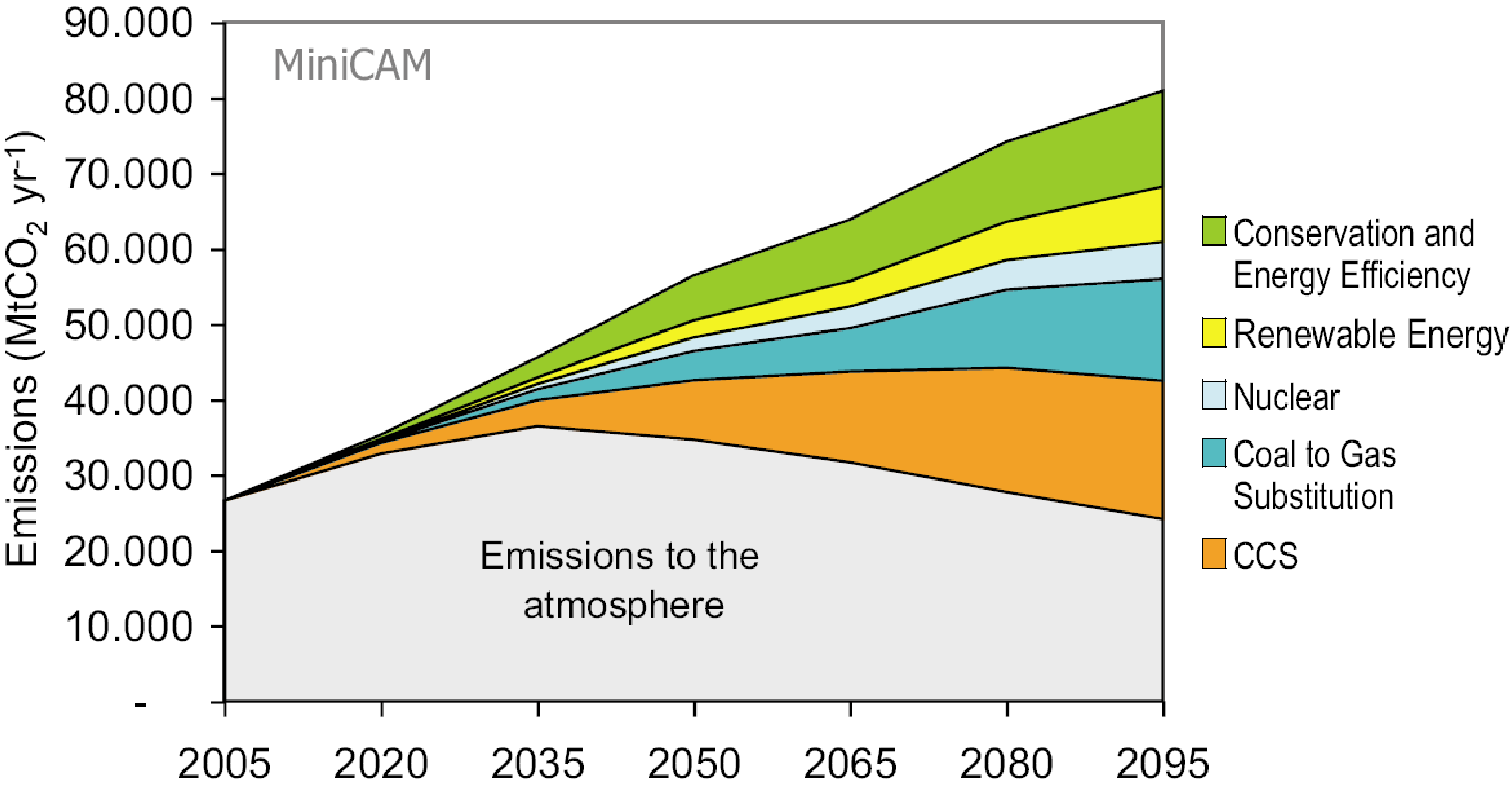
Source: IEA (2011)

IPCC Conclusions for Emissions Mitigation Potential

- CO_2 concentration is the highest in the last 650k years
- Global GHG emissions reduction challenge:
  - To cap CO_2 conc. at 450ppm → leading to temperature rise of 2.0-2.4°C;
  - To reduce 2050 emissions to ~75% of 2000 emissions → to target reducing annual global emissions to 5 Gt CO_2.

→So there is no ‘silver bullet’ to mitigate CO_2 emissions!

IPCC Conclusions for Emissions Mitigation Potential



Source: IPCC (2005)

- CCS are set of process technologies aiming to remove CO_2 from industry fluid stream and reroute it into a contained storage site.
- Capture
  - Power plants;
  - NG treatment;
  - Oil refineries;
  - etc
- Transportation
  - Pipelines;
  - Ships;
- Storage
  - Underground geological formations;
  - Ocean.
- *Although it is a relatively expansive process, O&G industry became specially interested on the storage technology in geological formations as an analogue to enhanced oil recovery technology.*

Main Carbon Capture and Storage Facilities

Country	Location	Capacity (Mt CO_2/year)	Start Year	Storage Type
USA (Texas)	Val Verde (Gas plant)	1.3	1972	EOR
USA (Oklahoma)	Enid	0.7	1982	EOR
USA (Wyoming)	Shute Creek	7	1986	EOR
Norway (North Sea)	Sleipner	1	1996	LGS
USA (North Dakota)	Great Plains	3	2000	EOR
Algeria	In Saliah	1	2004	LGS
Norway (Barents Sea)	Snohvit	0.7	2008	LGS
USA (Texas)	Century	8.4	2010	EOR
Total		**23.1**		

LGS: Long-term geological storage
EOR: Enhanced oil recovery

Source: IEA (2013)

Shell CCS Quest in Canada

http://www.youtube.com/watch?v=cZqEfupKlJs

Carbon Capture

Suitable CO_2 sources for Capture

- Large stationary point source (e.g., power generation plants, industrial processes, synthetic fuel production etc);
- High CO_2 concentration in the waste, flue gas or by-product stream (purity)
- Pressure of CO_2 stream
- Distance from suitable storage sites

Global large stationary CO_2 sources with emissions (> 0.1 $MtCO_2$/ year)

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Process		Number of sources	Emissions ($MtCO_2$ yr^{-1})
Fossil fuels	Power	4,942	10,539
	Cement production	1,175	932
	Refineries	638	798
	Iron & steel industry	269	646
	Petrochemical industry	470	379
	Oil & gas processing	Not available	50
	Other sources	90	33
Biomass	Bioethanol & bioenergy	303	91
Total		**7,887**	**13,466**

Technologies for CO_2 Capture

Three main technologies:

- Post-combustion capture: separation CO_2-N_2;
- Pre-combustion capture: separation CO_2-H_2;
- Oxyfuel combustion capture : separation O_2-N_2

	Post-comb. (flue gas)	Pre-comb. (shifted syngas)	Oxyfuel comb. (exhaust)
p (bar)	~1 bar	10-80	~1 bar
[CO_2] (%)	3-15%	20-40%	75-95%

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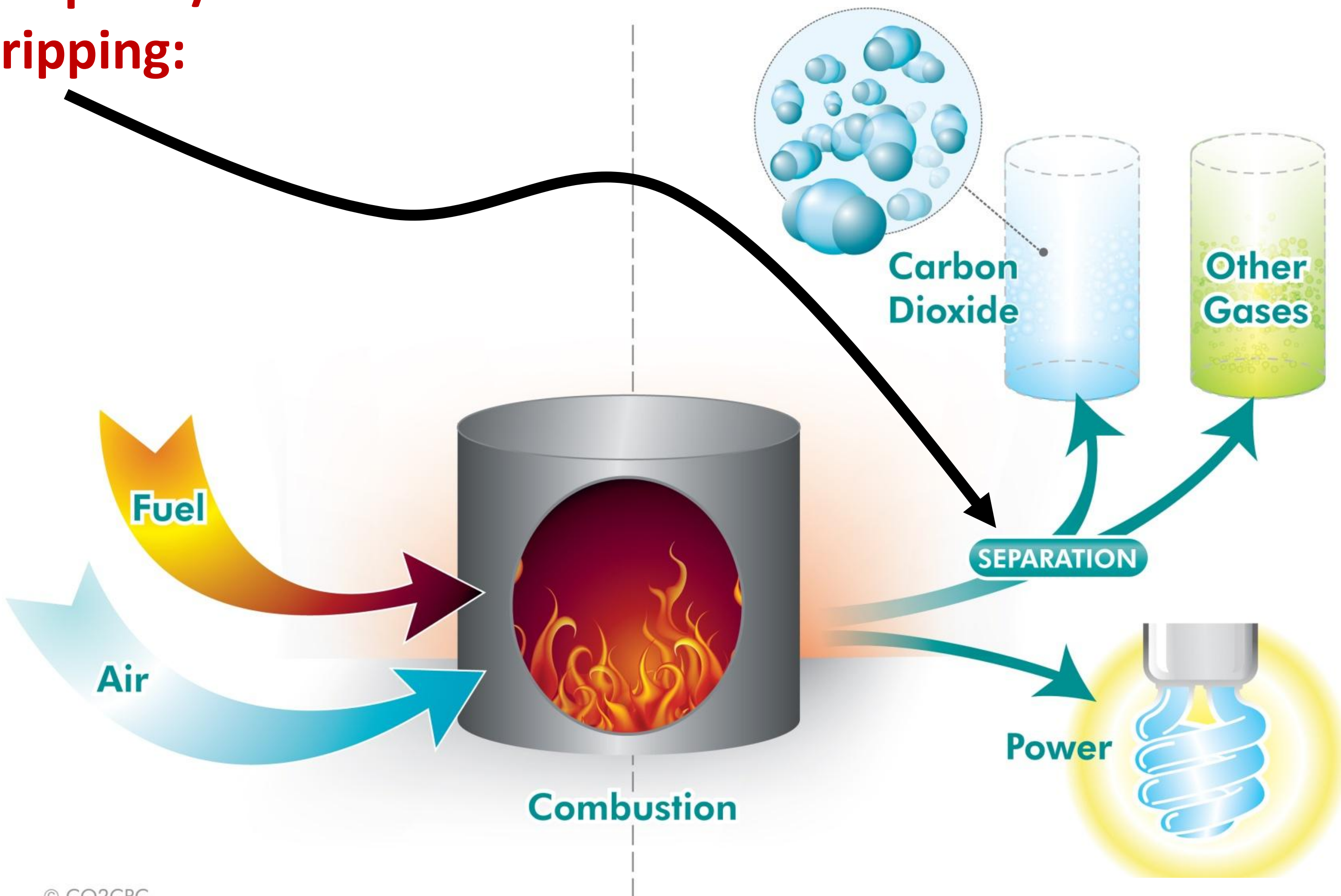
Technologies for CO_2 Capture: Post-Combustion

Absorption/ Stripping:



Source: http://www.co2crc.com.au/

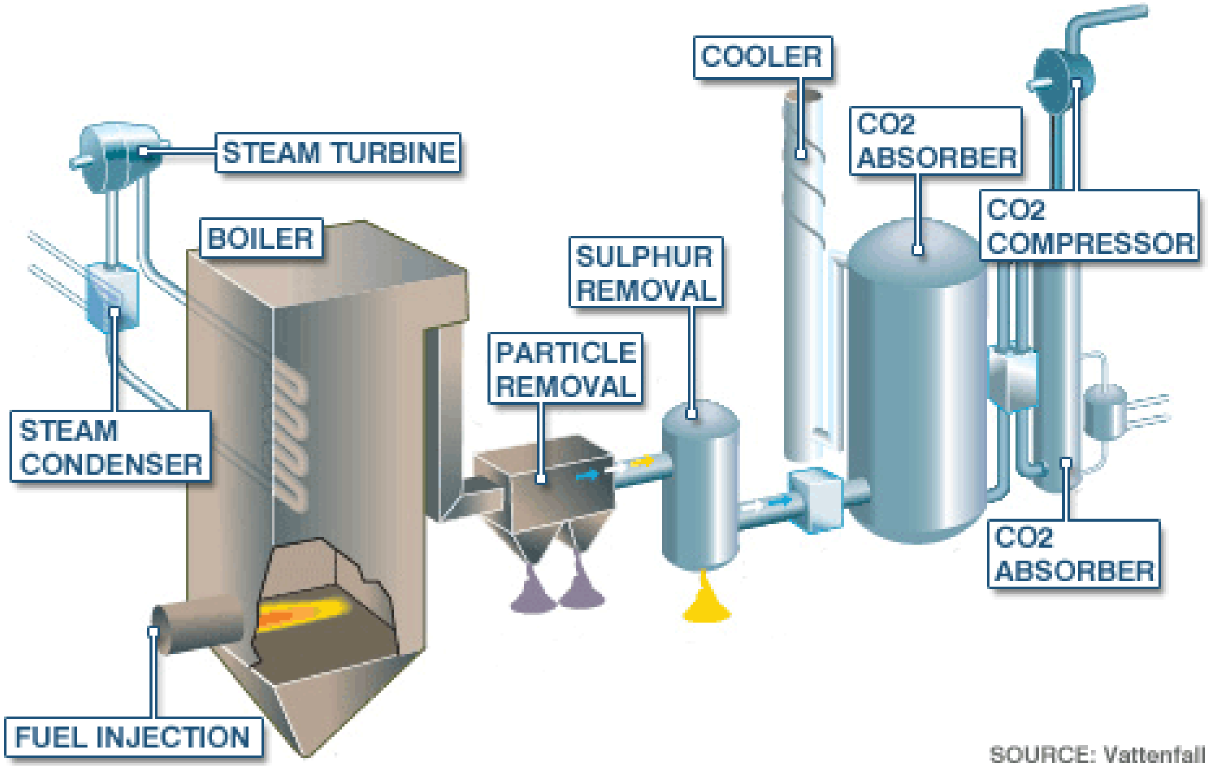
Absorption/Stripping:

$$CO_2 + OH\text{-}C_2H_4\text{-}NH_2 + B \rightarrow OH\text{-}C_2H_4\text{-}NH\text{-}CO_2 + BH + \text{Heat}$$

Ethanolamine (MEA)

- Absorption of CO_2 by MEA at 40°C
- MEA recovery by desorption at 120°C
- Reboiler provides heat to desorber in the form of steam from the boiler, reducing plant output and efficiency
- Optimize loading, operating temperature, minimize solvent losses.

Technologies for CO_2 Capture: Post-Combustion



- Flue gas cooled & brought into contact with amine solution
- CO_2 bound to amine solution & transported to stripper
- Chemical reaction binding CO_2 with amine reversible
- Amine solution regenerated in scrubber
- Captured CO_2 compressed & dehydrated

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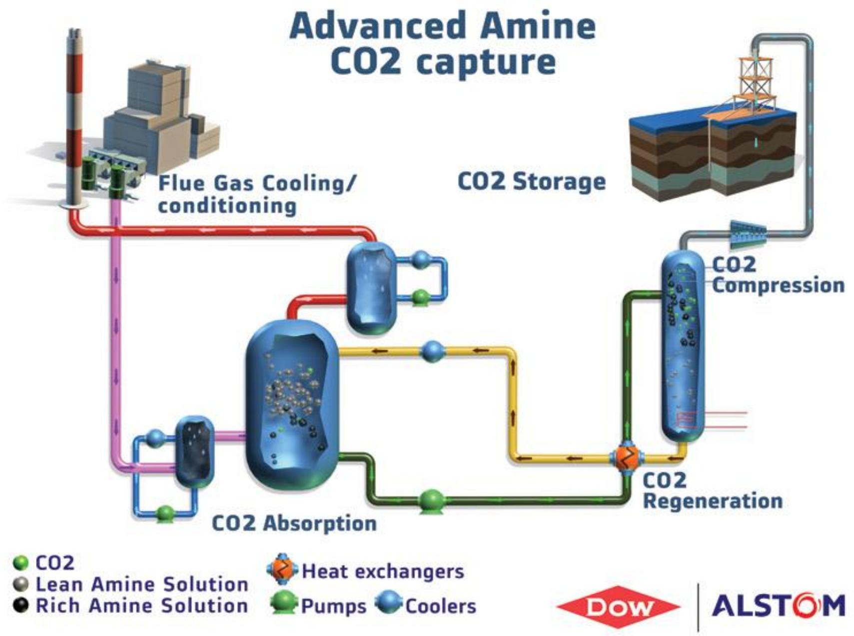
➢Pros:

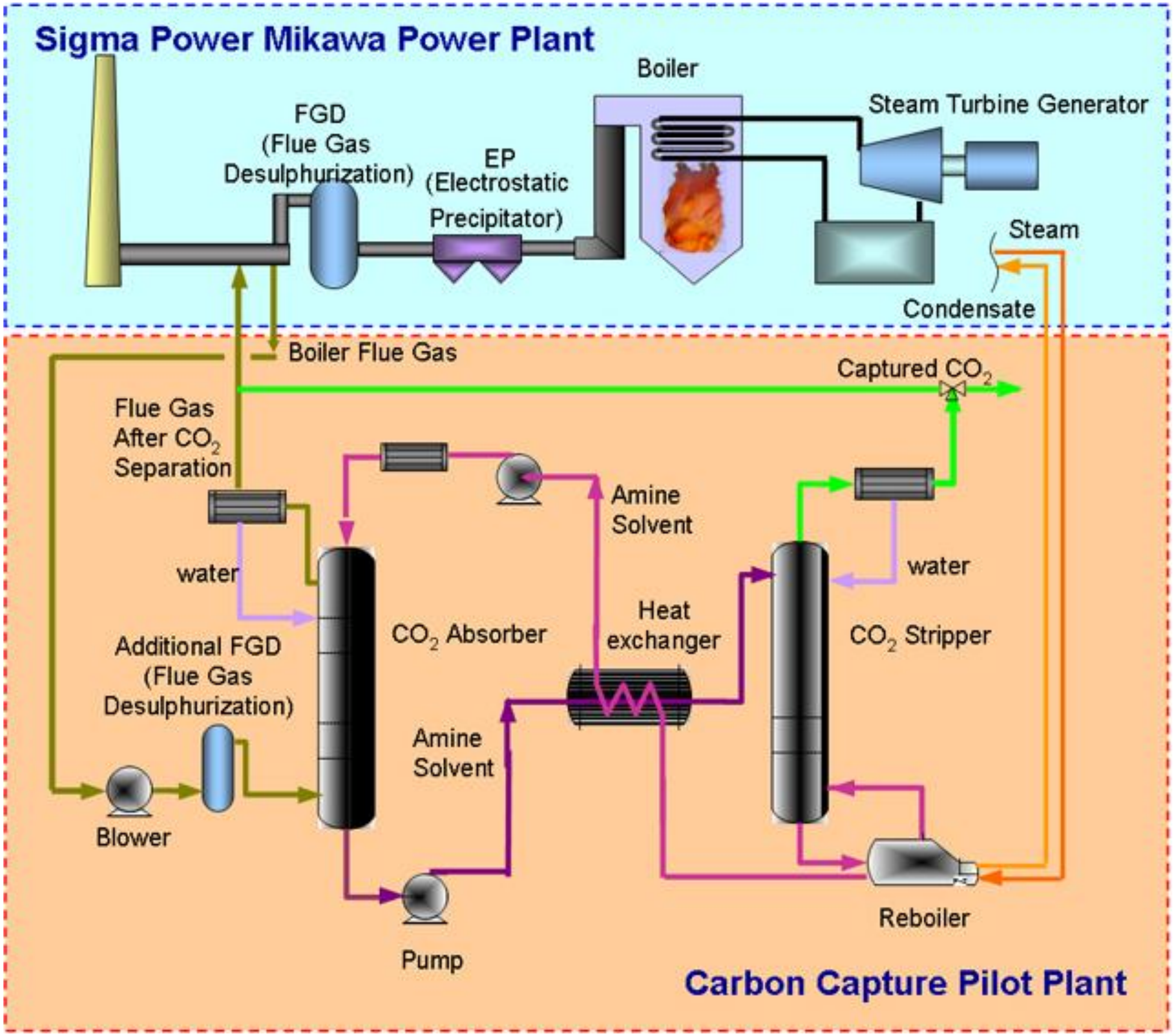
- Feasible to retrofit to current industrial plants and power stations.
- Existing technology - 60 years experience with amine solvents - but needs 10x scale-up.
- Currently in use to capture CO_2 for soft drinks industry.

➢Cons:

- High running costs – absorber and degraded solvents replacement.
- Limited large scale operating experience.

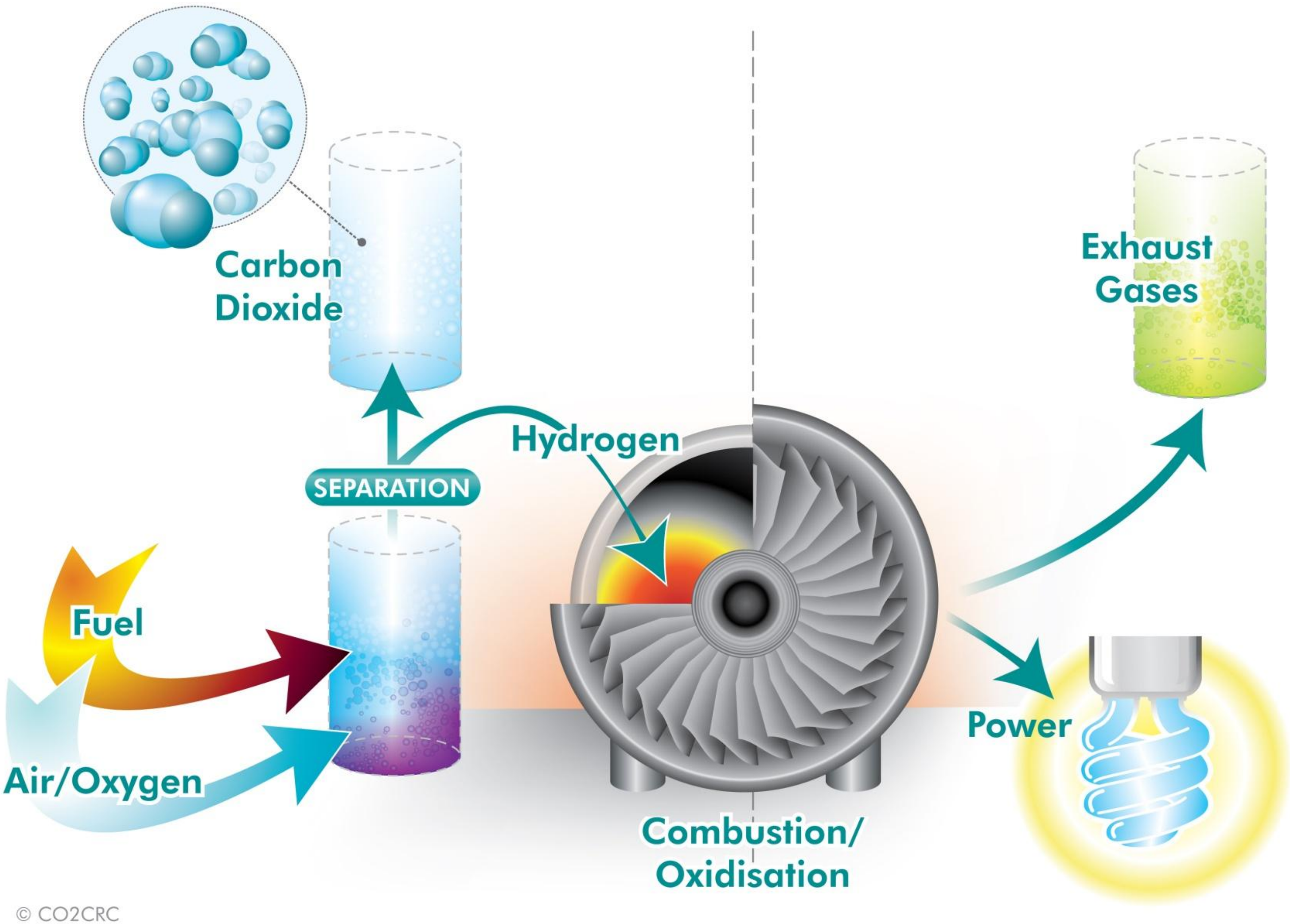


Technologies for CO_2 Capture: Post-Combustion



- Toshiba Technology.
- Pilot plant in Omuta City (Japan).
- Started on Sept 2009.
- Recovery energy: < 2.6GJ/t-CO_2 for 90% CO_2 capture with 12% of concentration).

Technologies for CO_2 Capture: Pre-Combustion



Source: http://www.co2crc.com.au/

Technologies for CO_2 Capture: Pre-Combustion

1st stage – to produce syngas (H_2 + CO)

Two routes:

Steam reforming – steam added to primary fuel

$$C_xH_y + xH_2O \longleftrightarrow xCO + (x + y/2)H_2$$

Partial oxidation of gaseous fuels (gasification)

$$C_xH_y + 0.5xO_2 \longleftrightarrow xCO + 0.5yH_2$$

2nd stage water gas shift reaction to convert the CO into CO_2

$$CO + H_2O \longleftrightarrow CO_2 + H_2$$

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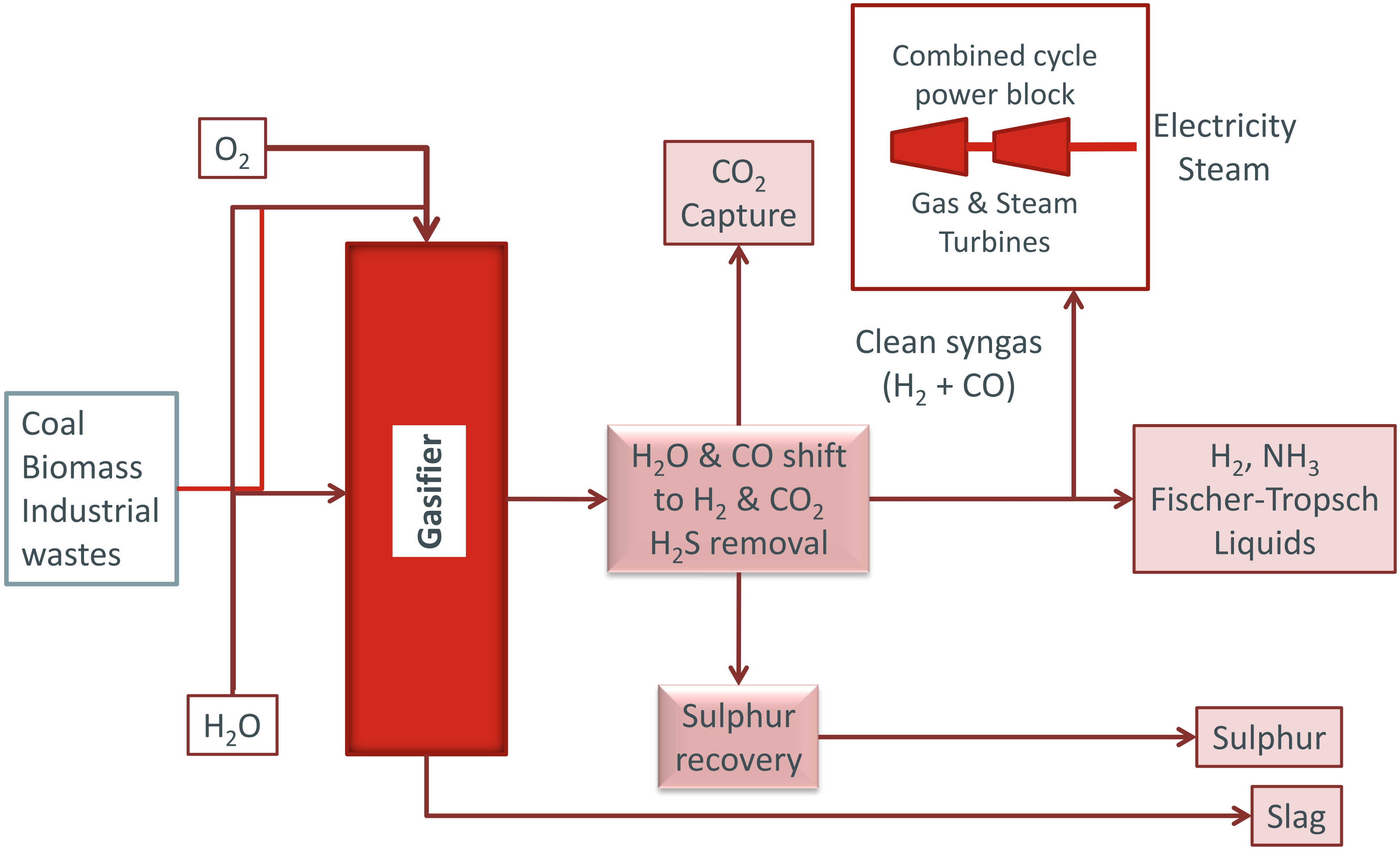
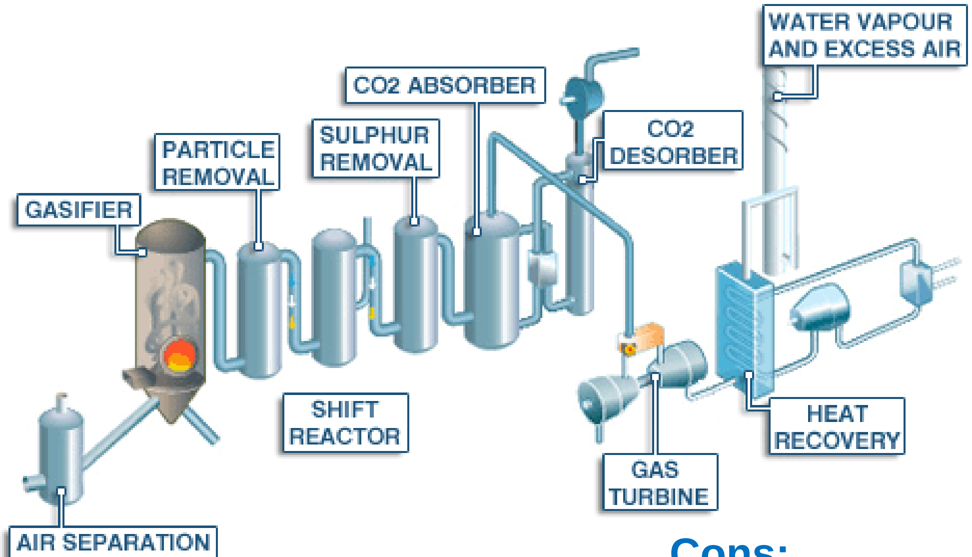
Technologies for CO_2 Capture: Pre-Combustion



Technologies for CO_2 Capture: Pre-Combustion



SOURCE: Vattenfall

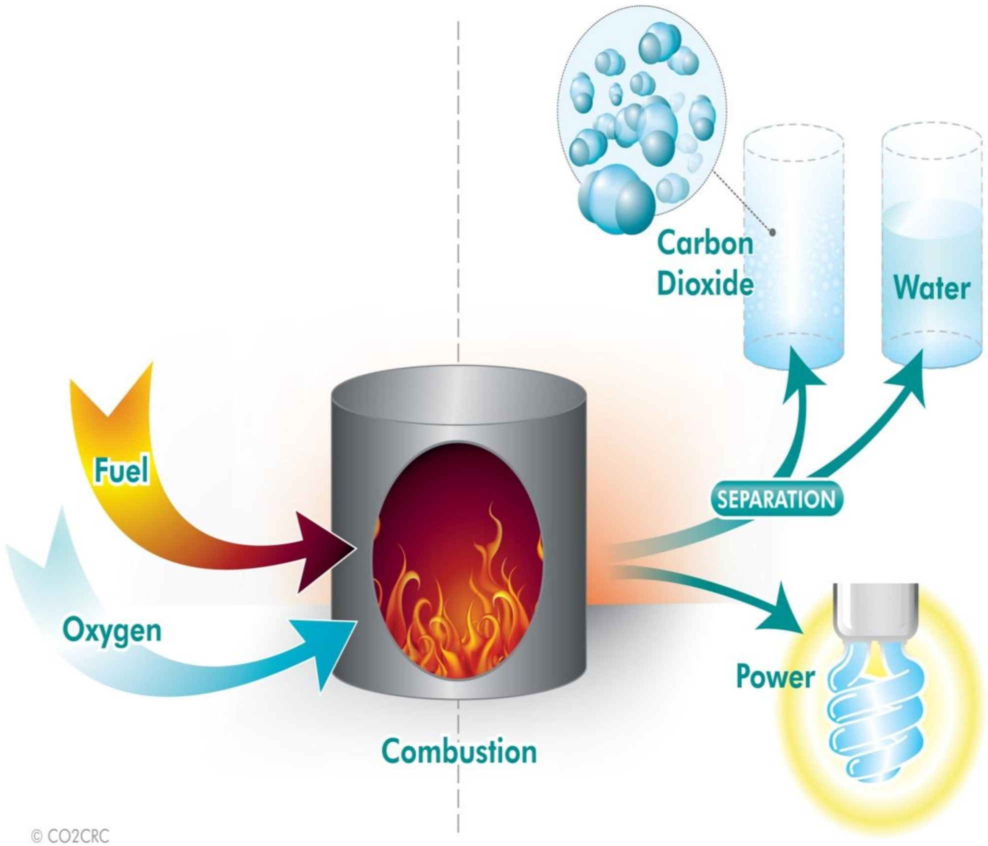
Pros:

- Proven industrial scale technology in oil refineries, but needs 3x scale-up for power plants.
- 90-95% of CO_2 emissions can be captured.
- Applicable to natural gas, and to coal fired Integrated Gas-Coal Combined Cycle (IGCC) power plants.
- Lowest technology risk, and may become the most efficient method.
- Can produce H_2 as transportable energy vector, or liquid fuels from coal - but penalties on efficiency

Cons:

- Requires a chemical plant in front of gas turbine
- High investment cost of dedicated new-build plant.
- High NOx emissions – will require expensive scrubbers.
- Efficiency of H_2 burning turbines is lower than conventional turbines.
- May be less flexible under varying electricity generation market requirement, so base load preferred

Technologies for CO_2 Capture: Oxyfuel



- Fuel is ‘burned’ in a mixture of nearly pure O_2 and CO_2 (recycled from the exhaust stream);
- The output from the combustion is the flue gas containing mainly CO_2 and H_2O;
- The steam is easily removed from the flue gas by condensation leaving a pure CO2 stream → suitable for compression, transport and storage.

Source: http://www.co2crc.com.au/

Technologies for CO_2 Capture: Oxyfuel

- Eliminates nitrogen from the flue gas by combustion in pure oxygen or mixture of pure oxygen and flue gas so NOx production reduced
- Combustion temperature of fuel in pure oxygen is too high so temperaure is controlled by proportion of process heat being recycled back to combustion chamber
- Combustion products mainly CO_2 + water vapour + O_2
- Combustion products cooled to condense water vapour giving 80 – 98% CO_2 depending on process & fuel
- Concentrated CO_2 compressed, dehydated, purified before transport & storage

Chemical Looping Combustion

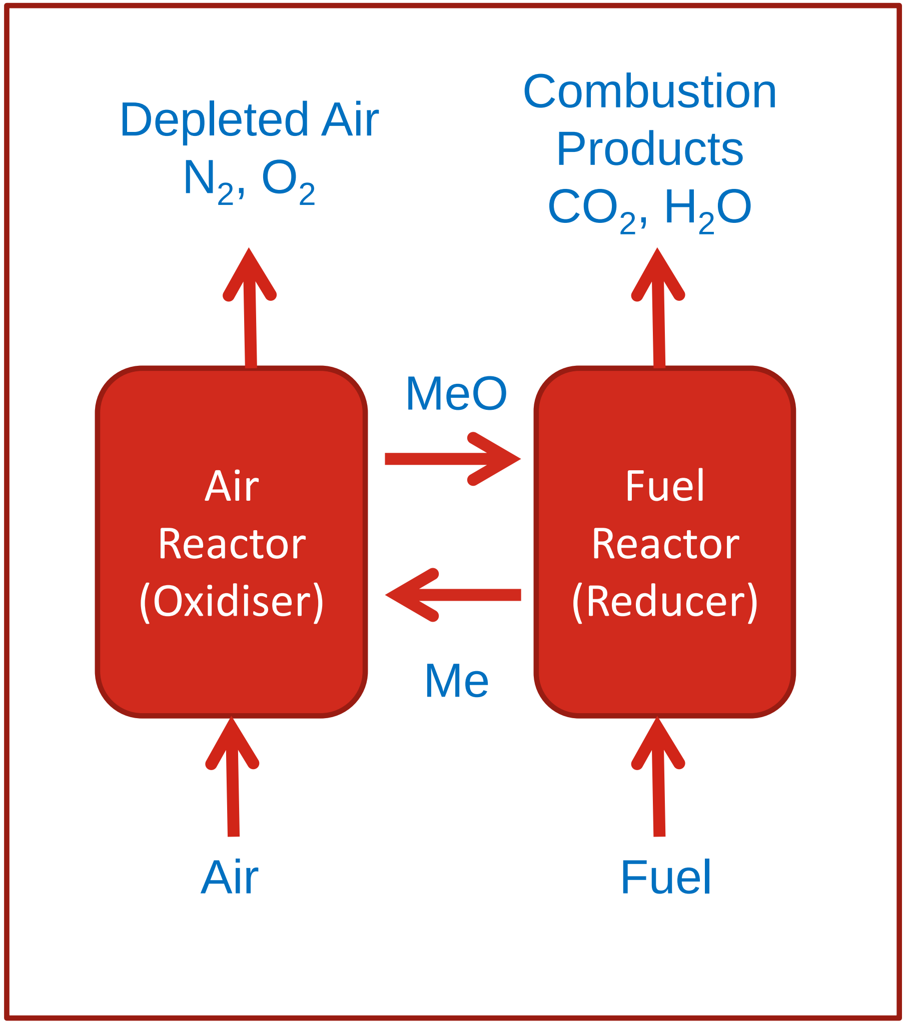
2 stage reaction of hydrocarbon combustion in 2 separate reactors:

- Air (oxidiser) Reactor
- Fuel (reducer) Reactor

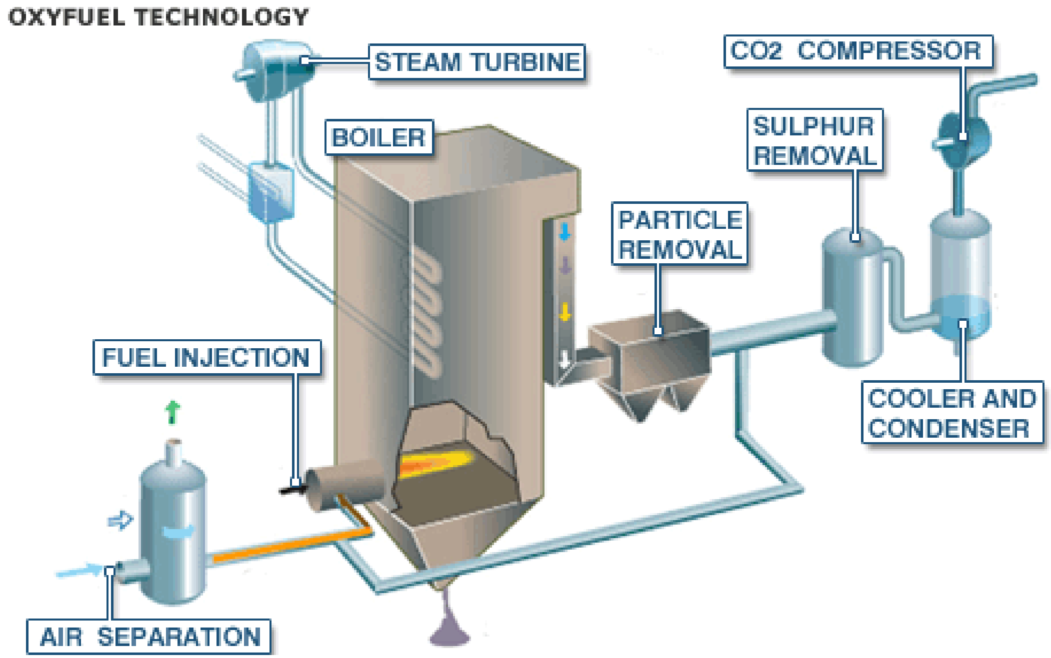
*Fuel burns in reducer therefore does not come into contact with air and avoids need for post-combustion capture

Uses metal oxide as a hydrogen carrier

- Metal particles reacted with air to give metal oxide
- Metal oxide particles react with fuel on fluidised bed reactor to produce:
  - Metal particles
  - CO_2 and water vapour
- Water vapour condensed leaving pure CO_2



Technologies for CO_2 Capture: Oxyfuel



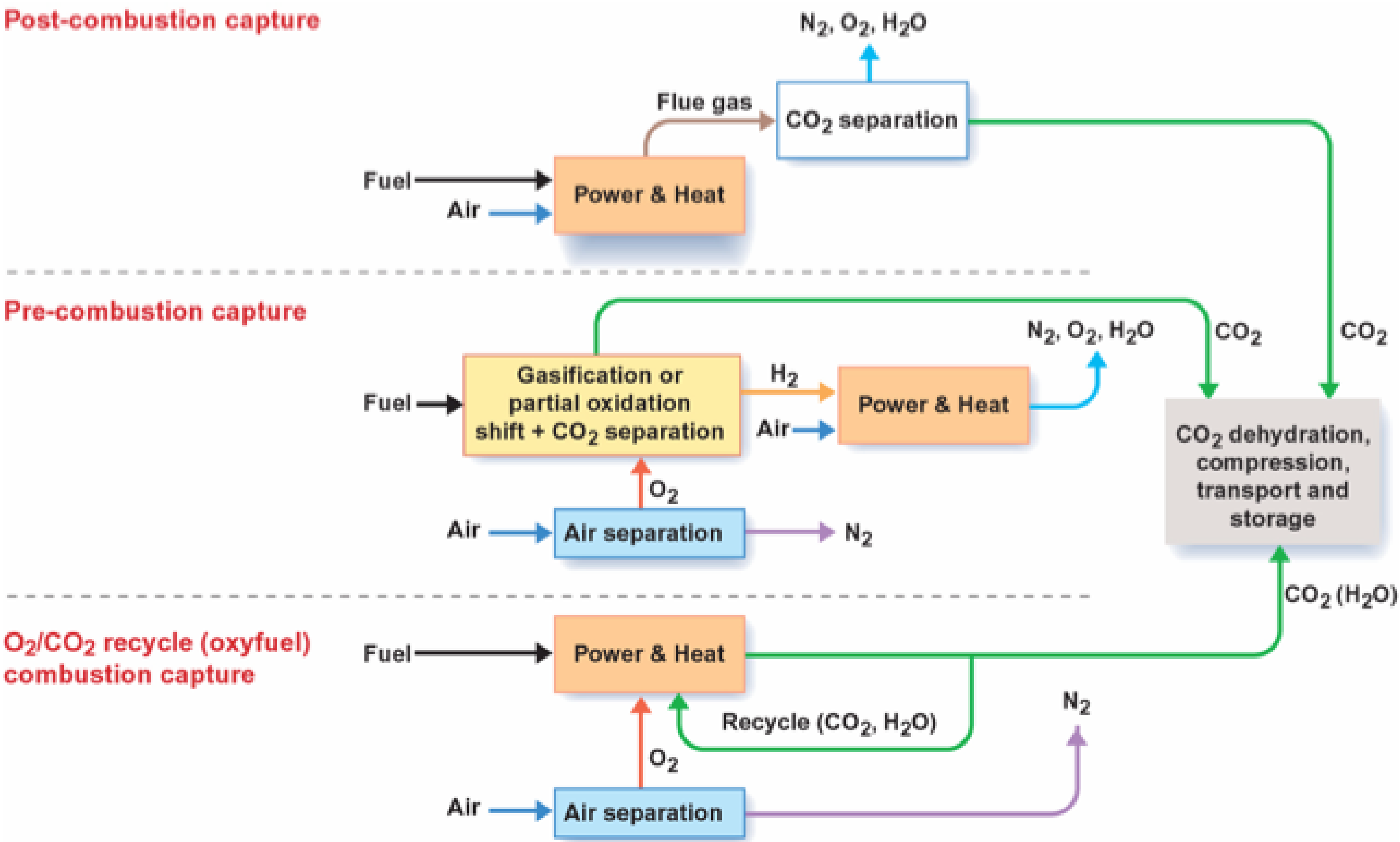
Pros

- Potential for 100% CO_2 capture.
- Few other harmful emissions due to more complete combustion.
- May be possible to retro-fit the oxy-fuel burners onto modified existing coal power plant

Cons

- High energy penalty without chemical looping combustion.
- Only at large development stage in 2007 - first Demonstration plants in planning

Technologies for CO_2 Capture: Summary



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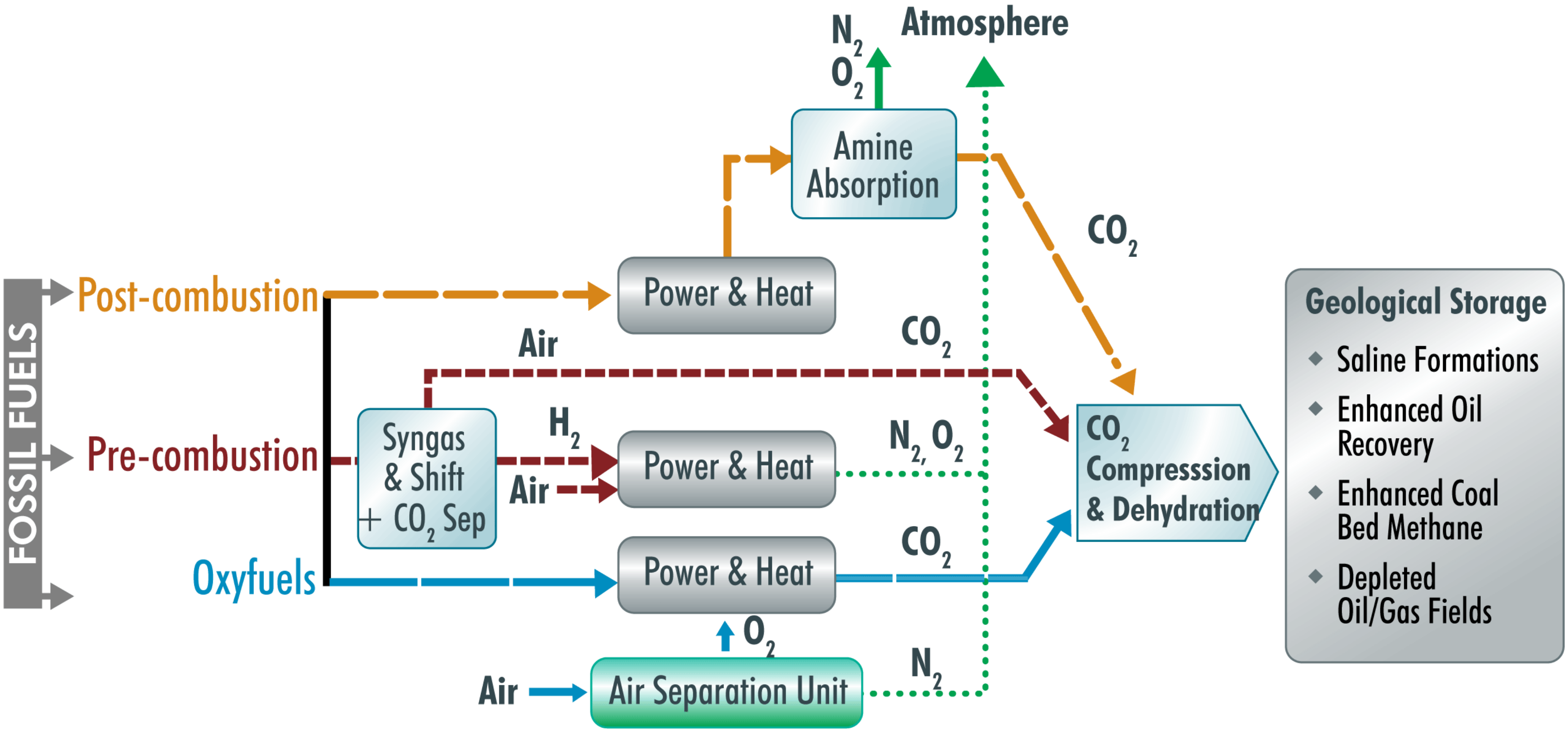
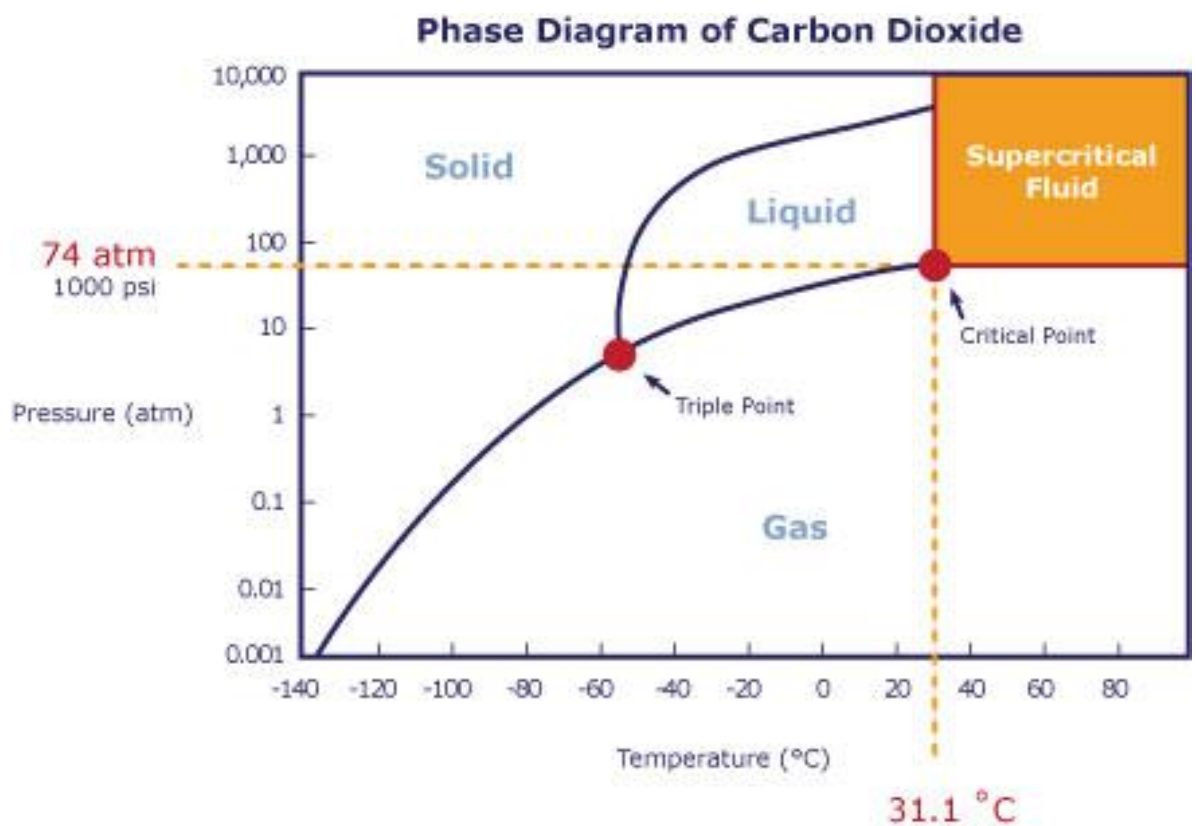


KEY: O_2 = Oxygen N_2 = Nitrogen CO_2 = Carbon dioxide H_2 = Hydrogen

Carbon Transport

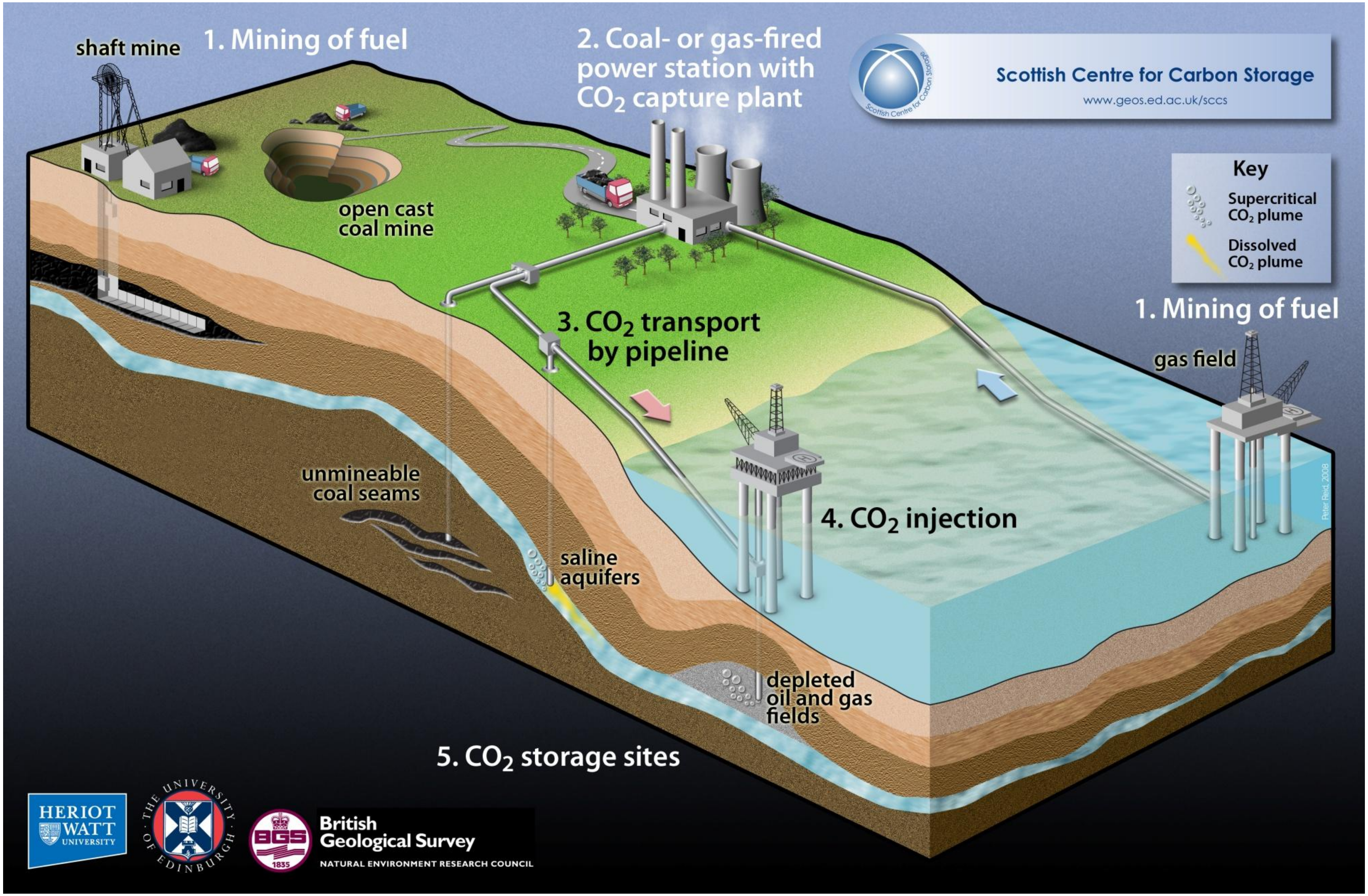
Technologies for CO_2 Transport

- Transport CO_2 → Temperature and pressure conditions need to be controlled to prevent solidification (i.e., phase change) and blockages.
- At $T>T_c$ and $P>P_c$, CO_2 behaves as a gas but has a very high density (e.g., at 100 atm and 45°C → 463 kg/m³ whereas at 1 atm and 20°C → 1.815 kg/m³).
- Two main methods:
  - Pipelines (similar to LNG): high-pressure (80-150 bar)
  - Ships: liquid (14 to 17 bar, -25 to -30°C)
    - Advantage: flexibility, avoidance of large investments
    - Disadvantage: high costs for liquefaction and need for buffer storage



Carbon Storage

Technologies for CO_2 Storage



Geological Storage

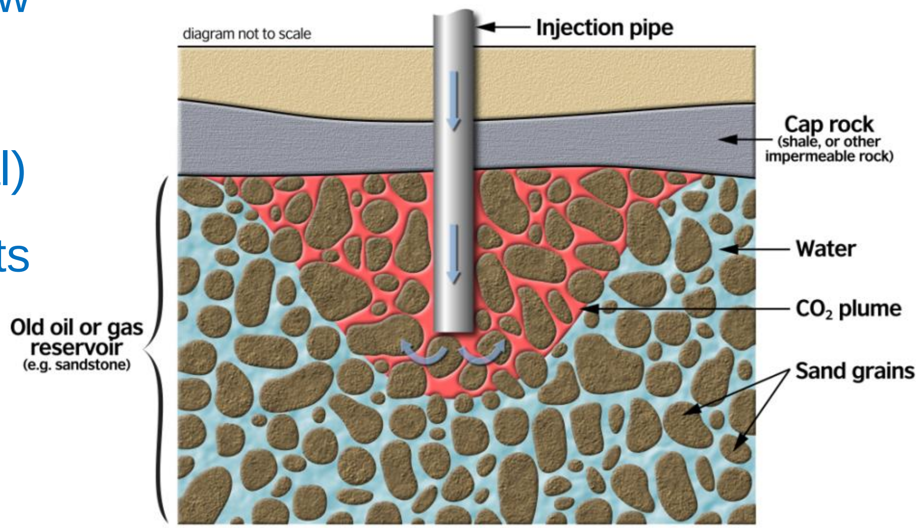
- Geological storage capacity at least 2,000 $GtCO_2$ mainly in oil and gas fields and in formations bearing saline water;
- Upper limit uncertain, especially in saline formations;
- Specific site characteristics need closer evaluation;
- CO_2 injection and reservoir engineering technology for depleted oil & gas fields and saline formations is mature and available;
- Monitoring of subsurface movement of CO_2 is being successfully conducted at several sites;
- Similarity with Enhanced Oil Recovery technology (injection of supercritical CO_2).

Geological Storage

- Fresh water aquifer
- Saline aquifer
- Depleted Oil and Gas Reservoirs

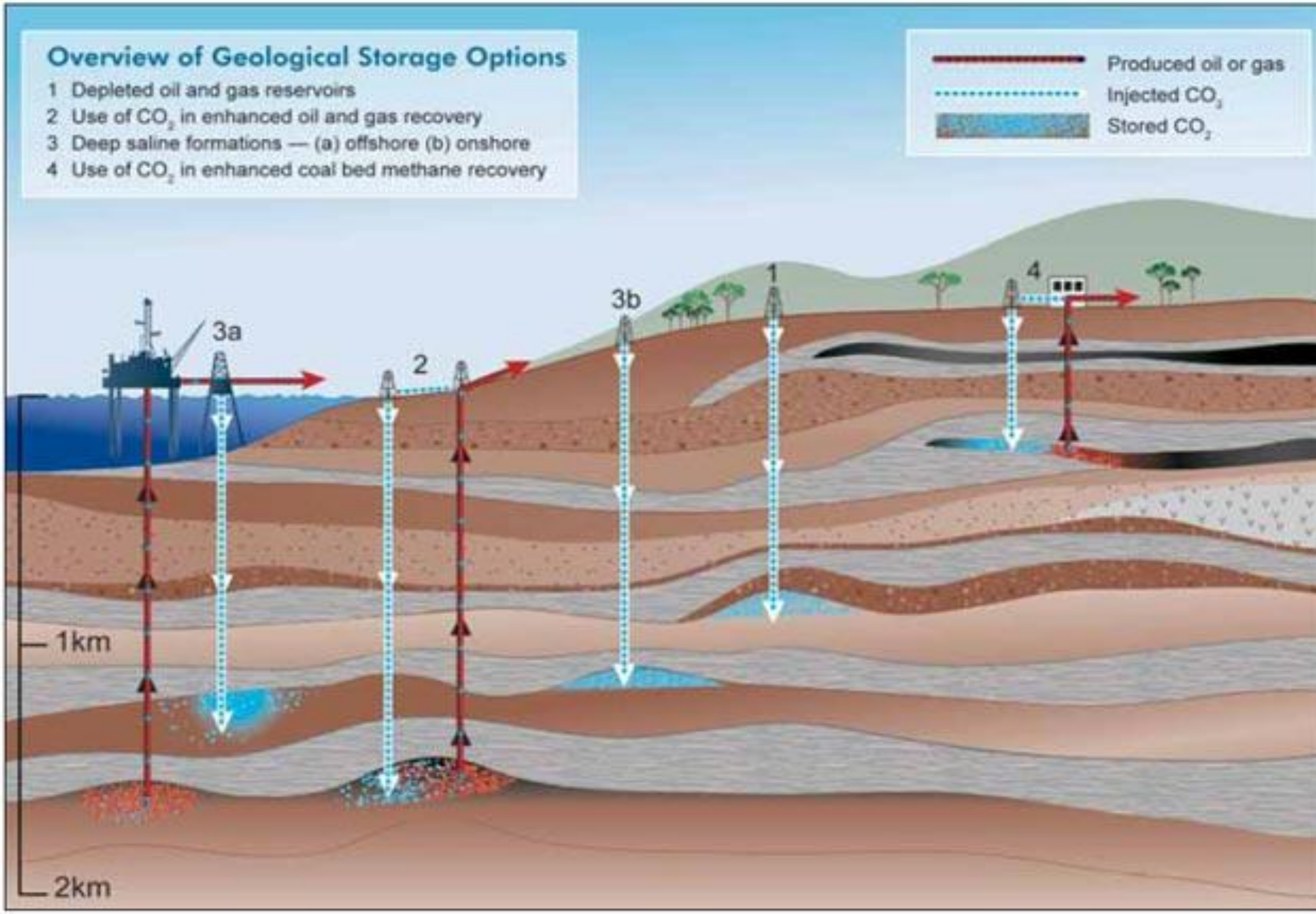
Criteria for CO_2 Geological Storage Site

- Reservoir: good porosity and permeability.
- Seal/caprock: low permeability, low porosity, preferably unfractured.
- Structural closure (although not essential)
- Formation below 800m: CO_2 exists in its dense phase
- Geologically stable area



Source: EU Directive 2009/31/EC on the geological storage of carbon dioxide.

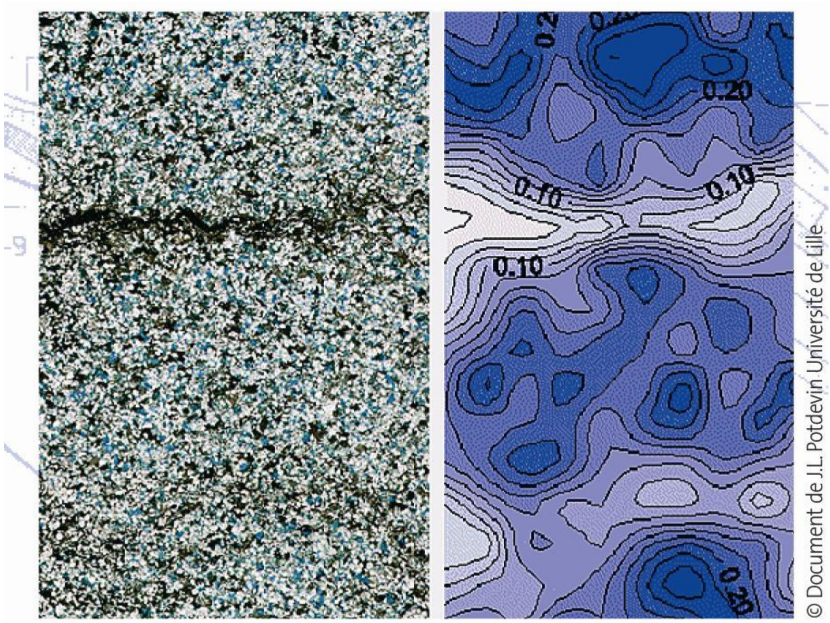
Technologies for CO_2 Storage



Source: IPCC

Storage Conditions

- Porous and permeable rocks that can contain (a mixture of) gas and liquid
- Rocks with pores of typically 5-30% of volume of the rock (with diameters of nm-mm)
- A sealing by a non permeable rock layer
- Typical Reservoir size is 0.05-50 km^3



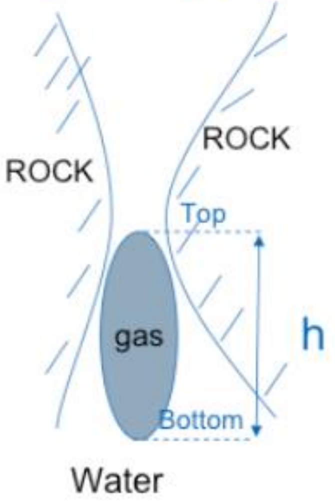
Porosity map: contour map (right) and corresponding sandstone cross-seciton.

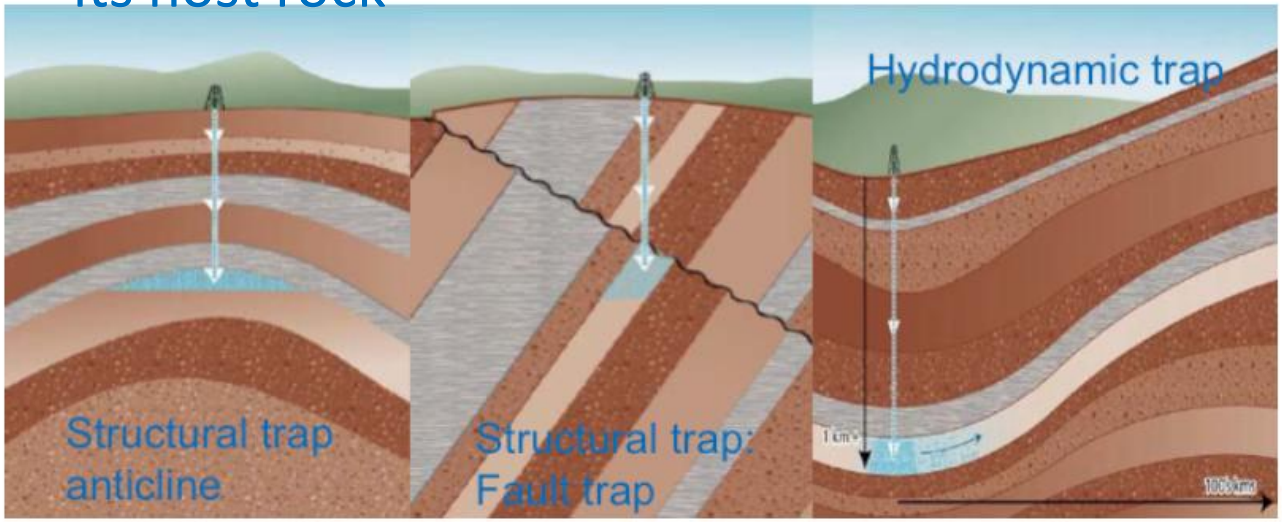
Immobilization and Trapping Mechanisms

http://www.youtube.com/watch?v=azLVjYij5U4&list=PL9C407E83C278B36F

Immobilization and Trapping Mechanisms: *Physical*

- Physical blocking by
  - structural traps (anticlines, unconformities or faults)
  - stratigraphic traps (change in type of rock layer)
- Hydrodynamic trapping by extremely slow migration rates of reservoir brine
- Residual gas trapping by capillary forces in pore spaces
- Negative buoyancy in case CO_2 is denser than its host rock





Immobilization and trapping mechanisms: *Chemical*

- Adsorption onto coal or organic-rich shales: permanently reduced mobility
- Mineralization into carbonate mineral phases: permanently reduced mobility
- Solubility trapping: CO_2 dissolved in formation waters forming one single phase: greatly reduced mobility

Technologies for CO_2 Storage

The different types of storage			
	CO_2 Capacity (in Gt)	Advantages	Disadvantages
Hydrocarbon reservoirs	930 Gt	Trapping structures impermeable to non-reactive gases. Well-known structures. Economic potential through EOR.	Generally far from CO_2 emission sites. Storage capacities often limited.
Deep saline aquifers	400 to 10,000 Gt	Widespread geographic distribution and vast storage potential. Facilitates the search for storage sites close to the sources of CO_2 emissions. Water unfit for drinking.	Poorly characterized to date.
Unmineable coal seams	40 Gt	Near CO_2 emission sites. Economic potential through methane recovery.	Injection problems due to the poor permeability of coal. Limited storage capacities.

Technologies for CO_2 Storage: Main Facilities

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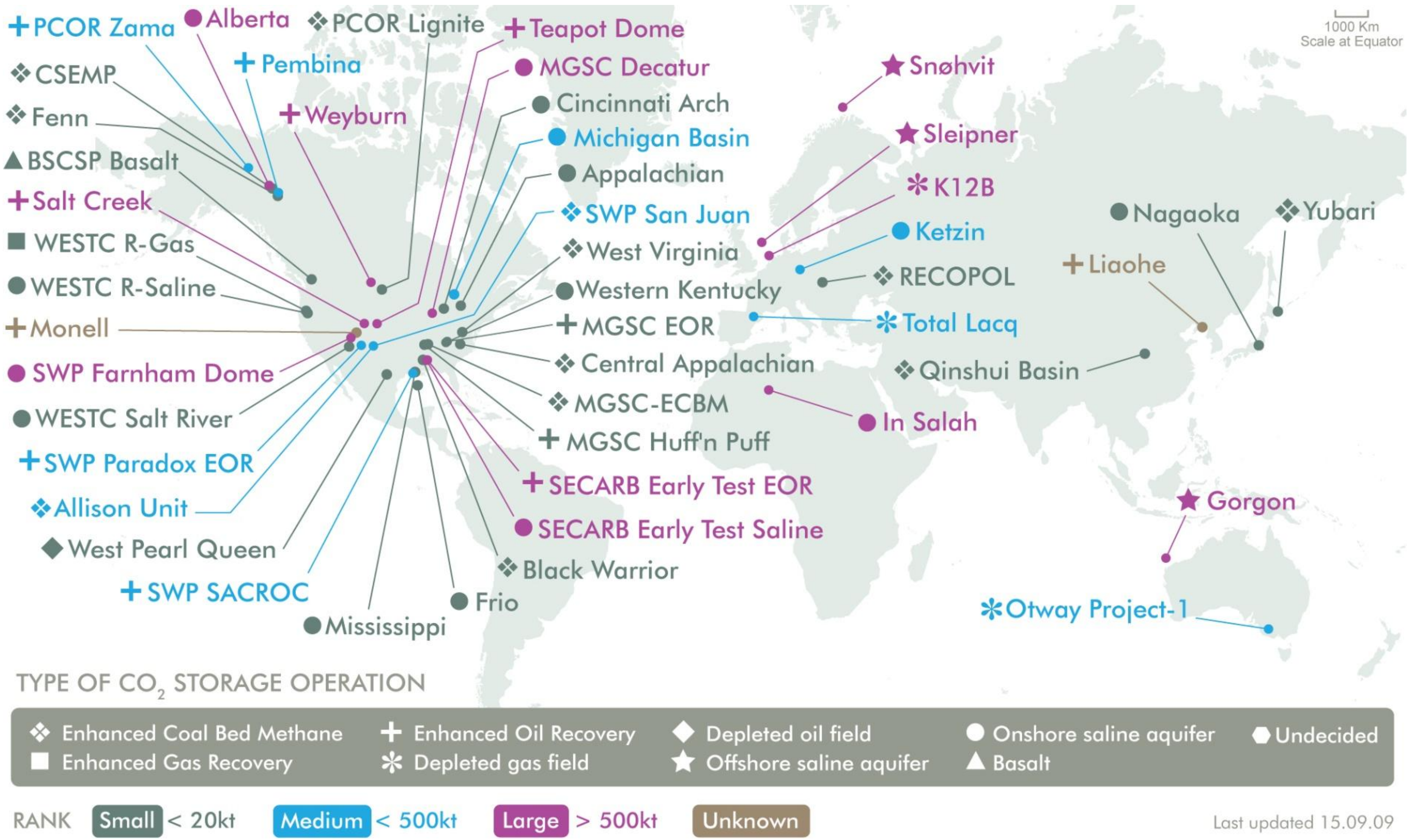

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Total		**23.1**		

LGS: Long-term geological storage
EOR: Enhanced oil recovery

Source: IEA (2013)

- Leakage of CO_2 (and also CH_4) to atmosphere;
- Stress (and overpressure) in the geological structures can cause micro-seismicity leading to small earthquakes;
- Migration of CO_2 plumes, displacing brines from the chosen geological formation to others that may contain fresh water (e.g., aquifers);
- Decrease soil's and water's pH causing (a) calcium dissolution, (b) increasing in water hardness, and (c) release of metals (trace);
- Thus monitoring the site is crucial to assess the conditions of the CO_2 plume migration and the reliability of the traping mechanisms.

Technologies for CO_2 Storage: Long-Term

- CO_2 dissolution in brine:

$$CO_2 + H_2O \rightarrow H^+ + HCO_3^-$$

- Calcium carbonate dissolution:

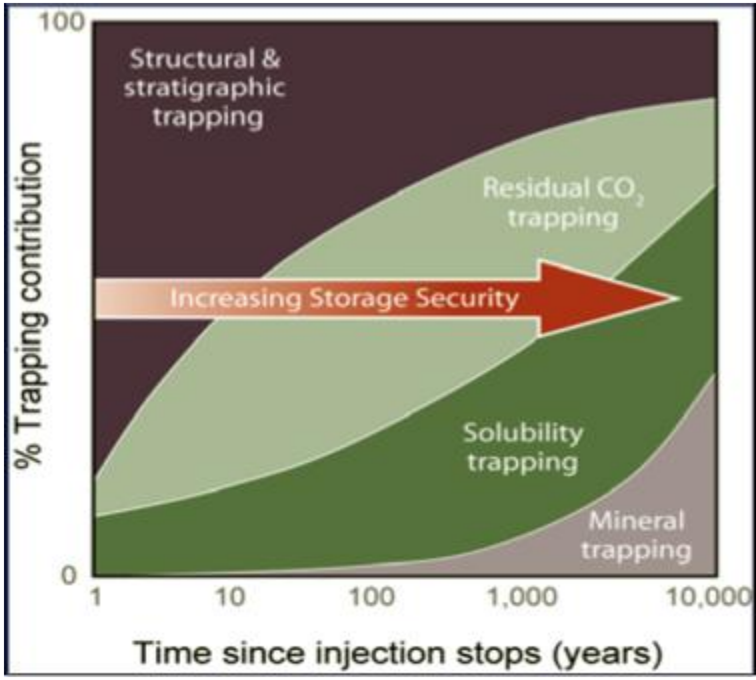
$$CaCO3 + H^+ + HCO_3^- \rightarrow Ca(HCO_3)_2$$

- Mineral precipitation:

$$(Ca, Mg, Fe)^{+2} + HCO_3^- \rightarrow (Ca, Mg, Fe)\,CO_3 + H^+$$

$$CaAl_2Si_2O_8 + 2H^+ + H_2O \rightarrow Al_2Si_2O_5(OH)_4$$

- CO_2 dissolves into the reservoir fluids
- $CO_2 + H_2O$ is denser than H_2O
- CO_2 is 'slowly' sequestrated by the minerals
- Through time $\rightarrow$ low probability of CO_2 leakage



Conclusions

- Increase of energy demands → leading to larger GHG emissions;
- There is no easy solution for the CO_2 emission problem;
- CCS is one of the methods to mitigate GHG emissions along with low-carbon energy sources;
- Several technologies for ***Capture;***
- Options for CO_2 transport: ships or pipelines;
- CO_2 can be stored for a very long time (10000 yr) under high pressure and low temperature conditions;
- Linkage with EOR technologies.
- Several storage projects have already started
- Leakage and other risk should be monitored carefully

Additional Reading

- M.E. Boot-Handford *et al.* (2013) "Carbon Capture and Storage Update", *Energy & Environmental Science*, published online on Sept/13 (**DOI:** 10.1039/C3EE42350F).
- N. MacDowell *et al.* (2010) "An Overview of CO2 Capture Technologies", *Energy & Environmental Science*, 3:1645-1669 (**DOI:** 10.1039/C004106H).
- B. Nykvist (2013) "Ten times more difficult: Quantifying the carbon capture and storage challenge", *Energy Policy*, 5:683-689 (**DOI:** 10.1016/j.enpol.2012.12.026).
- EU Directive 2009/31/EC on the geological storage of carbon dioxide (http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0114:0135:EN:PDF).
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