Carbon Capture and Storage (and Utilisation)

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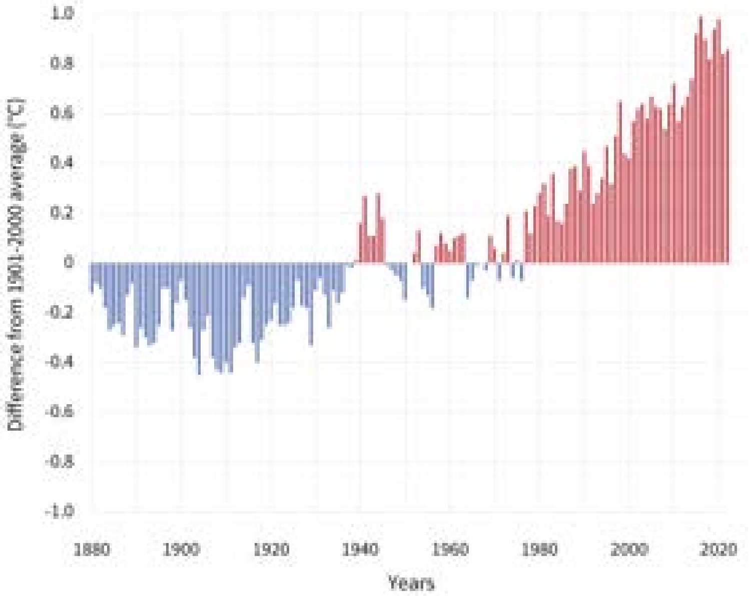
Course outline

1. Background
2. Introduction of CCS technologies
3. Post-combustion CCS: case study
4. Challenges of CCS
5. Future opportunities: CCU (optional)

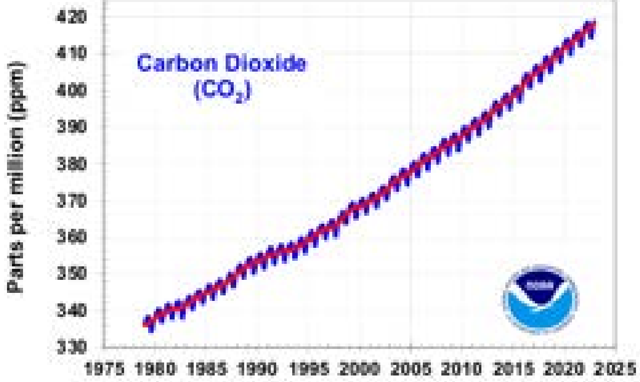
1. Background

Climate change

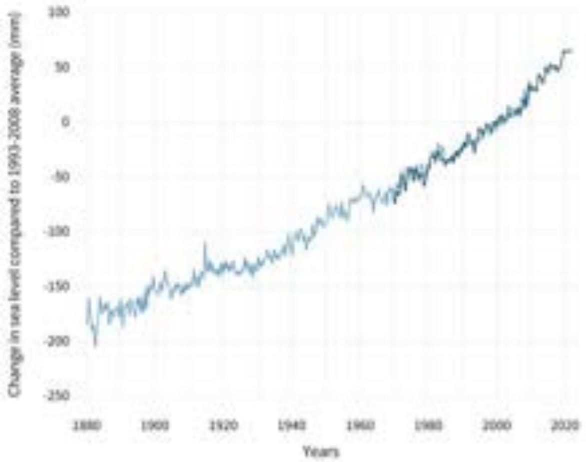
Global warming



Increasing atmospheric CO_2 concentration

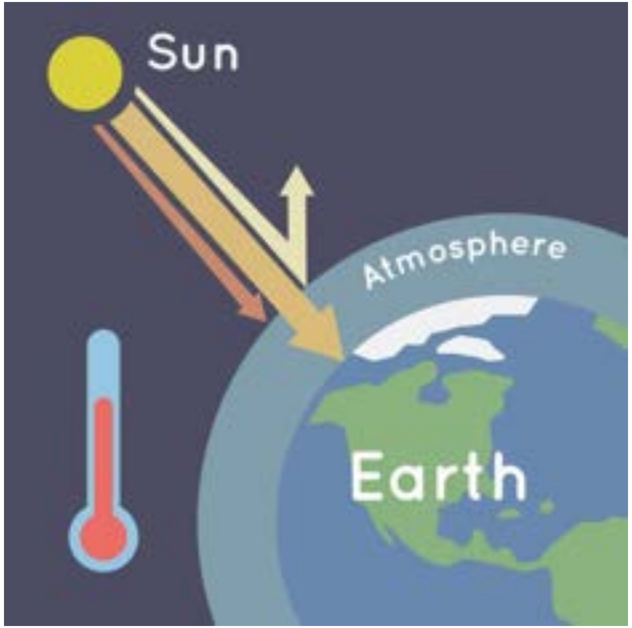


Rising sea levels

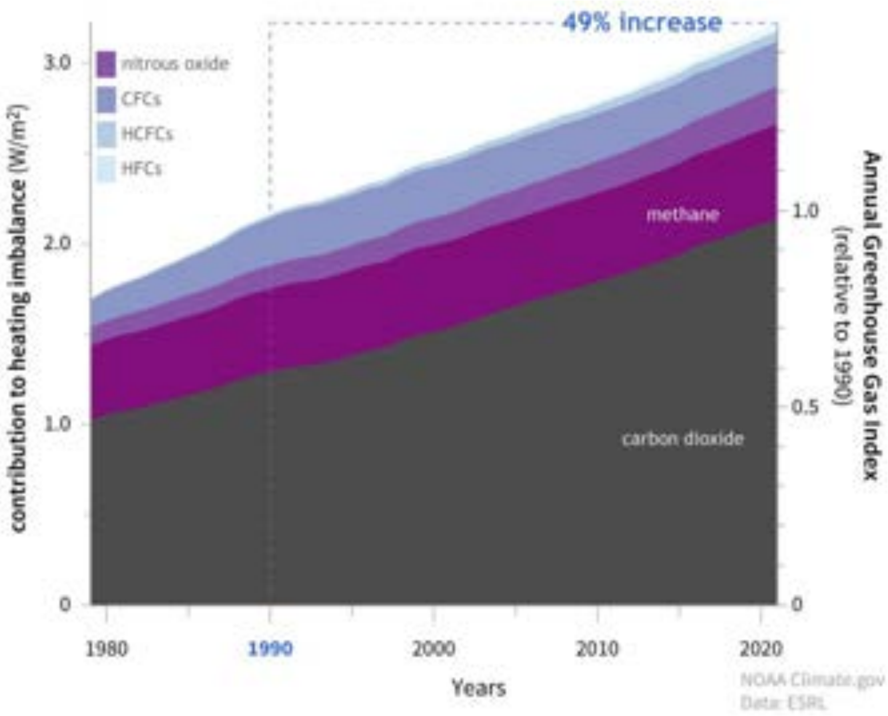


Source of data: NOAA

Greenhouse gas effect

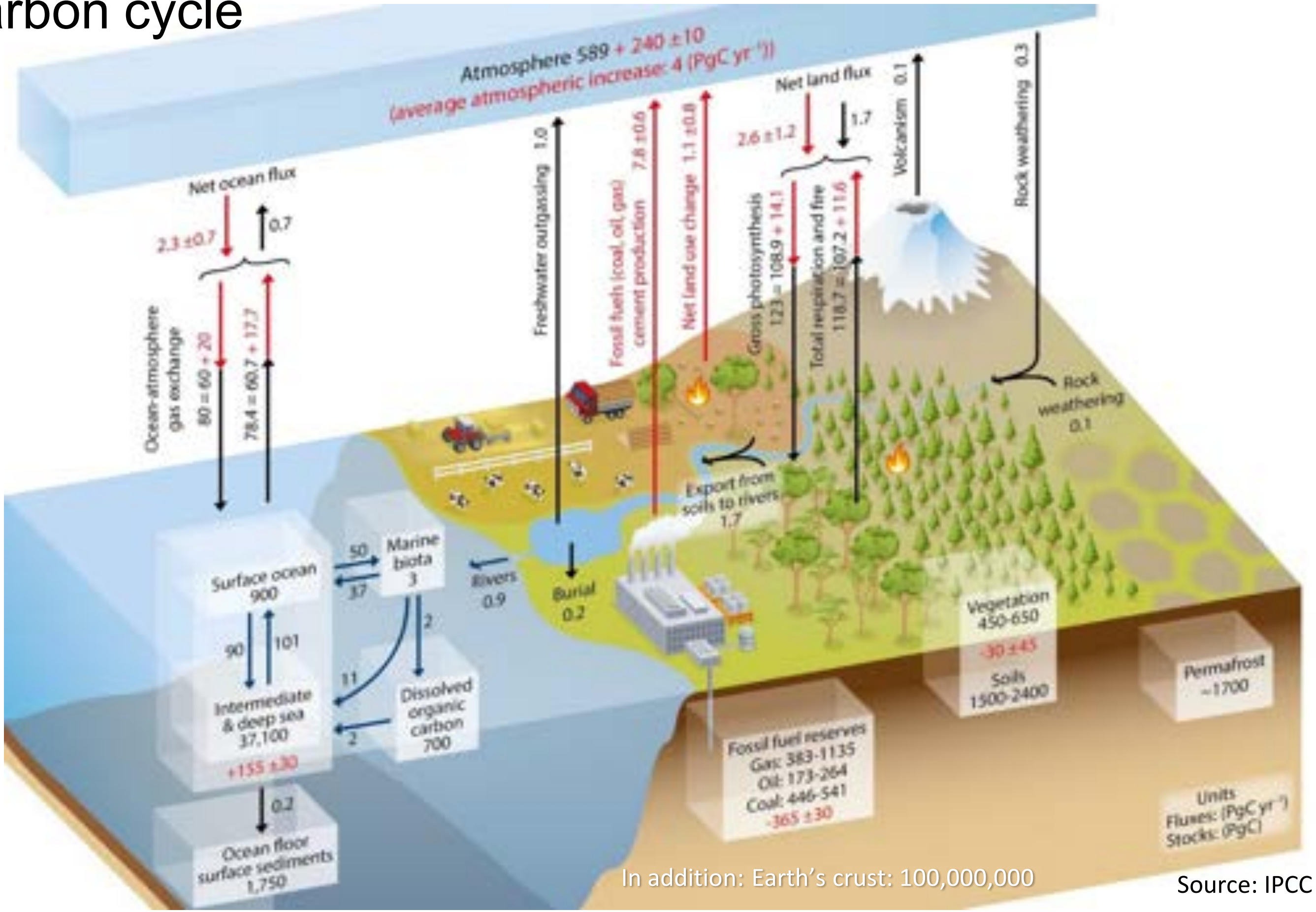


The Greenhouse losing its balance



Source of data: NOAA

Earth's carbon cycle



In addition: Earth's crust: 100,000,000

Source: IPCC (2014)

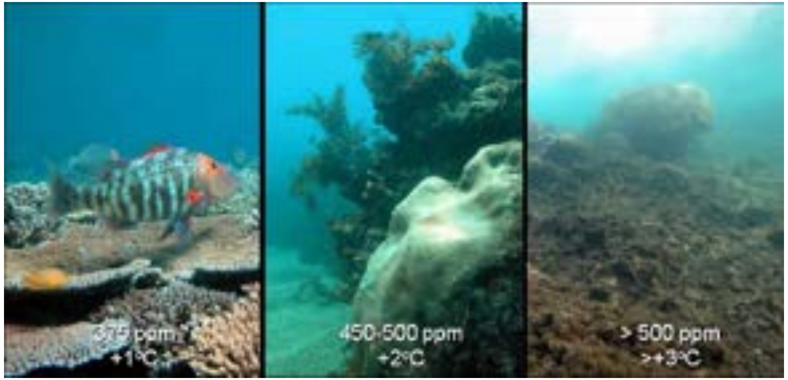
Climate change is more than global warming

Diminishing polar ice caps

Extreme weather events

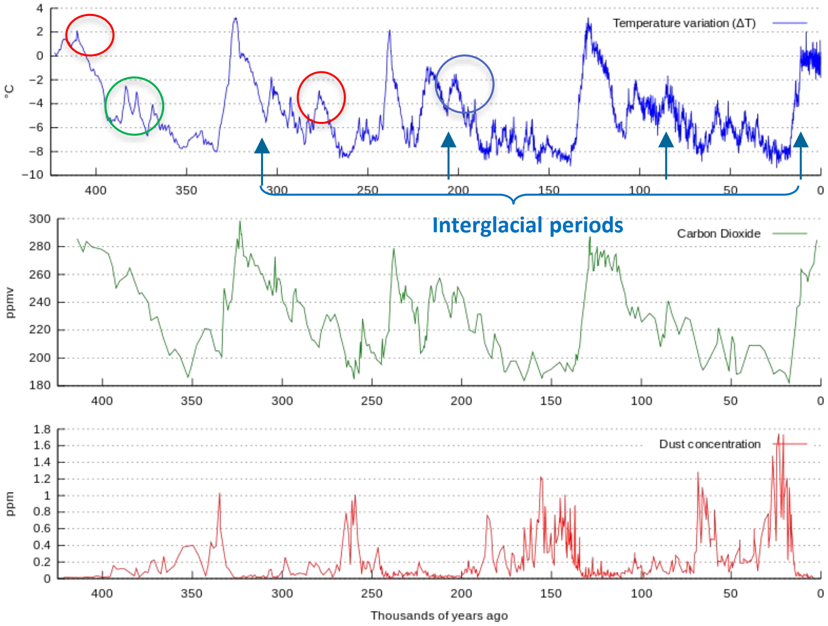
Retreating coastlines

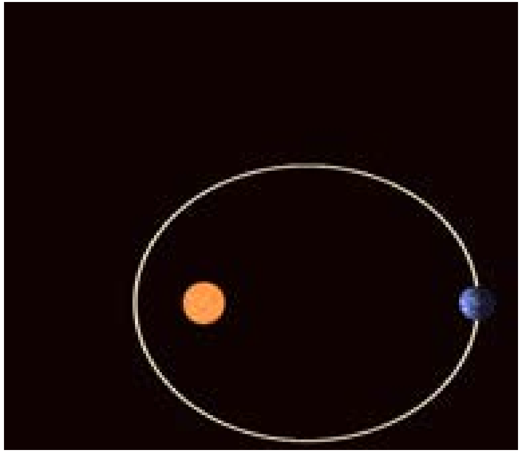
Destruction of ecosystems



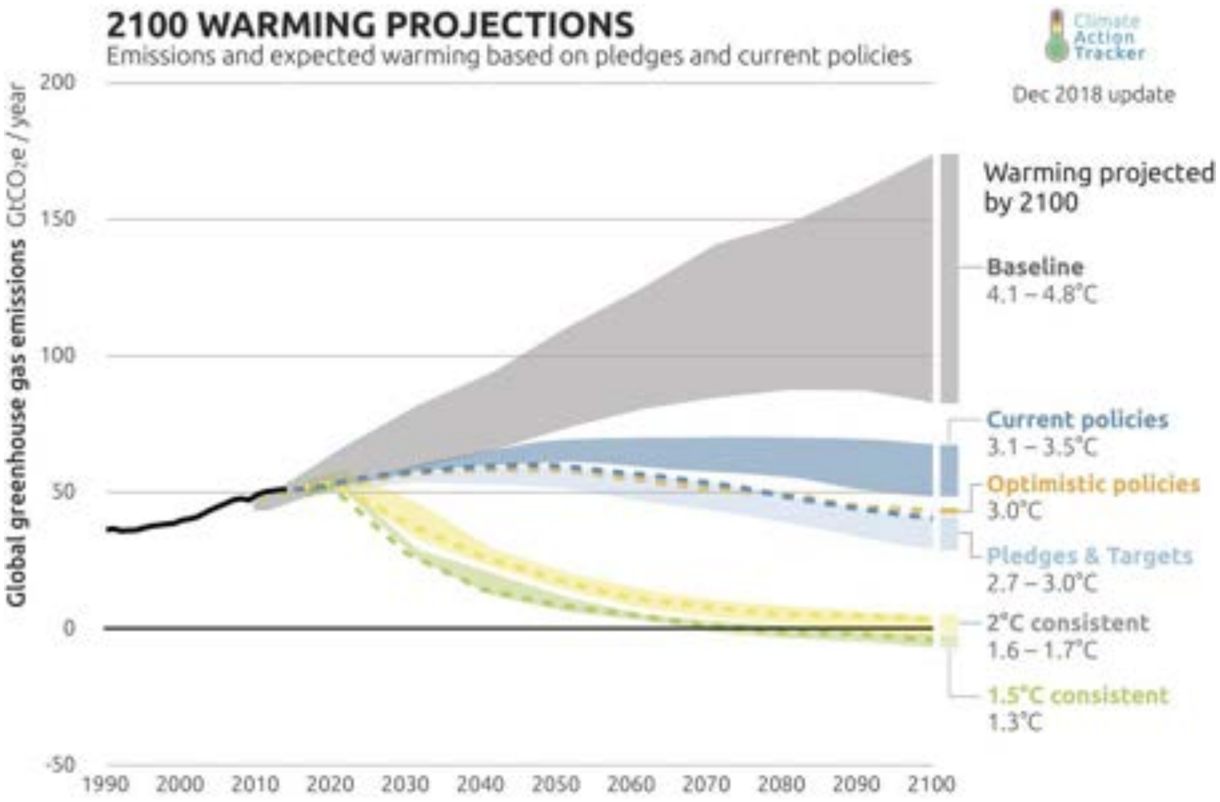
Climate change is not new

- Geological reasons
- Astronomical reasons
- The speed of climate change matters





Climate change projections



Consequence of inadequate climate action

- Achieving net-zero ASAP is the pre-requisite to control global warming to within 1.5 °C
- Current policies and industrial efforts are inadequate to achieve the “1.5 °C target”.
- Every additional 0.5 °C means
  - 2.6 x more extremely hot days
  - 10 x more ice-free days in the Arctic
  - 2.3 x reduction in agriculture output
  - 41% reduction of coral reefs and their ecosystems
  - 2 x reduction in fishery harvest

There is no single solution

Circular economy

Energy efficiency

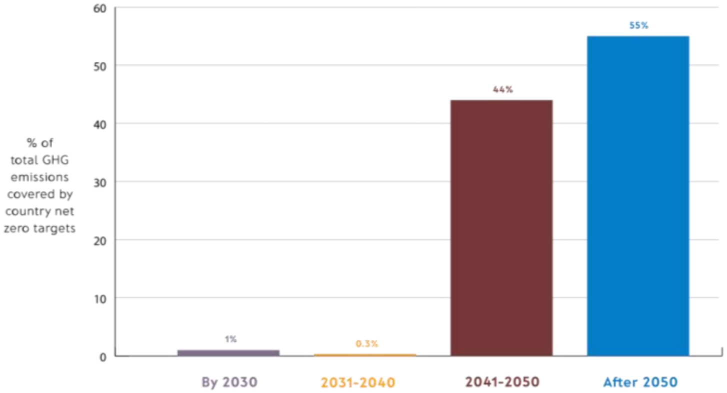
Renewables

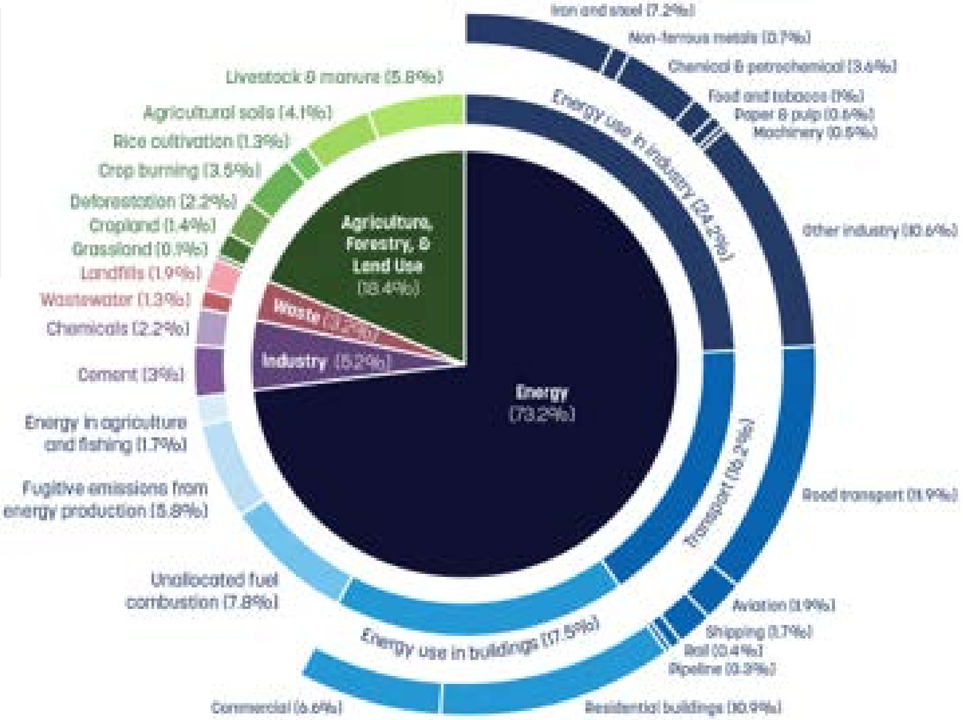
CCUS

Radiation management

Reforestation & afforestation

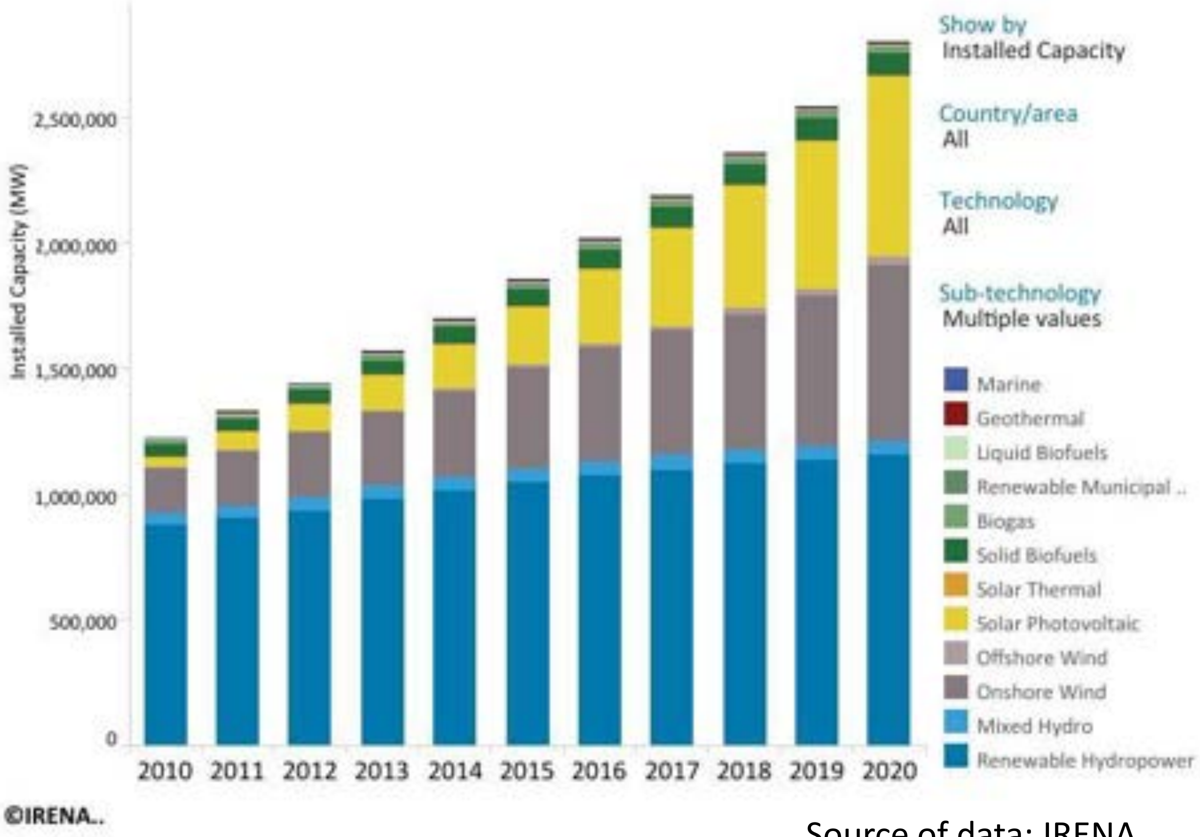
Global pledge to net-zero





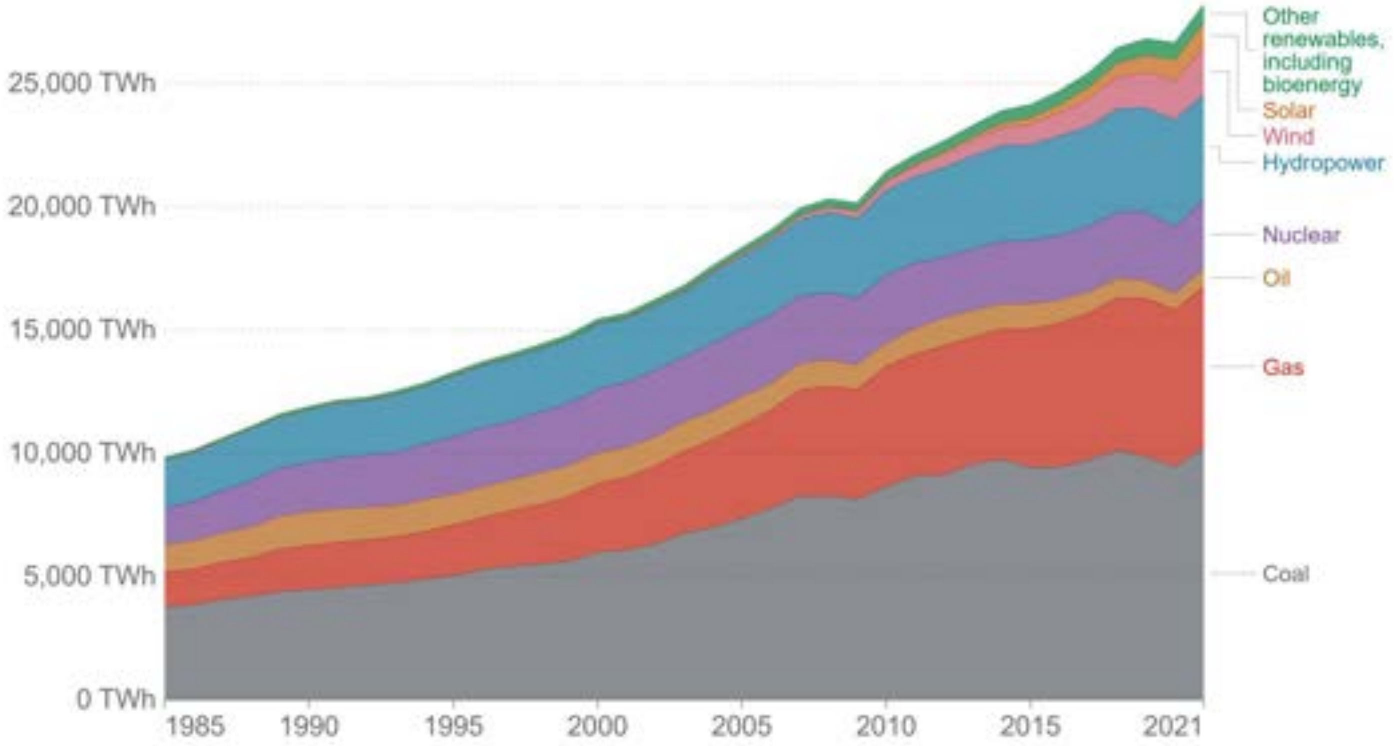
Sources: zerotracker.net; WorldBank.org

Development renewable energy



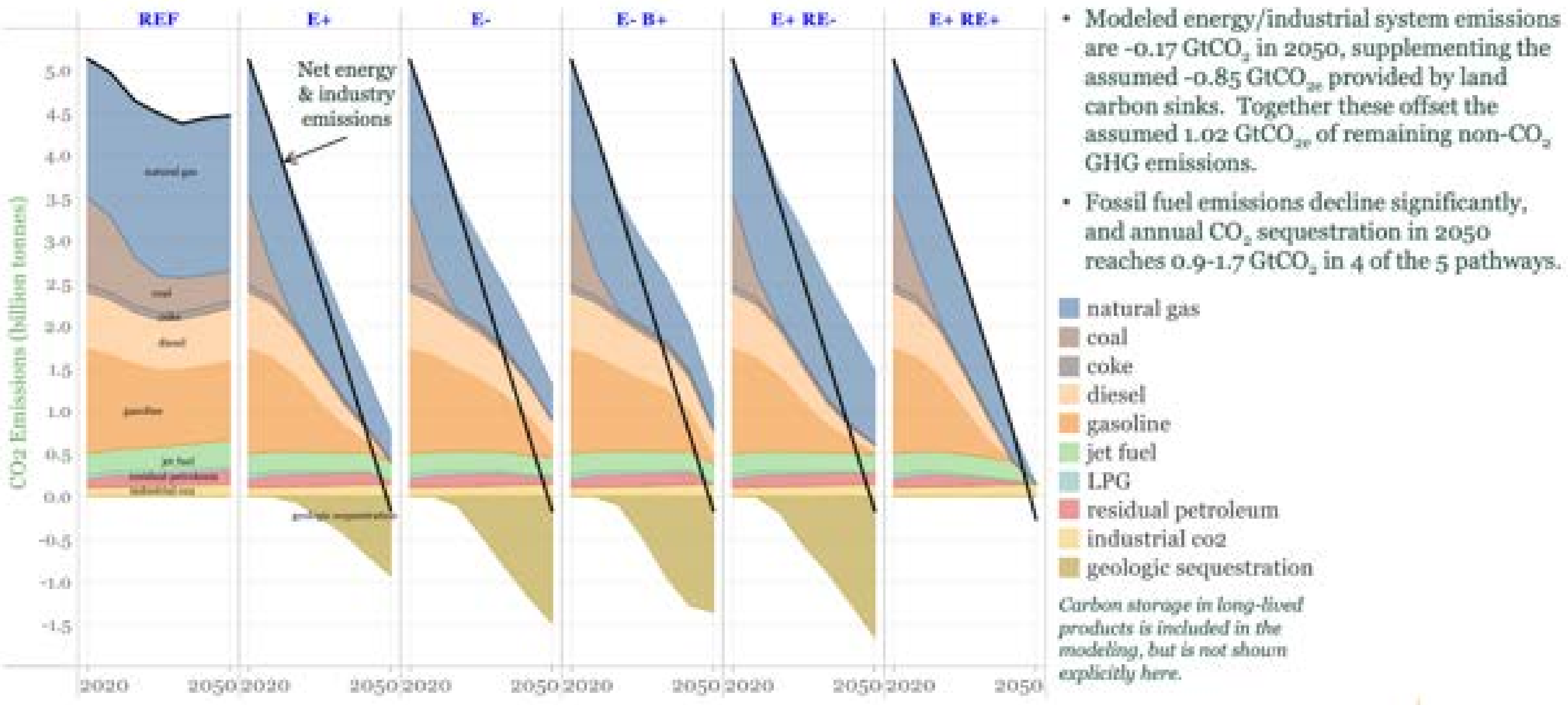
Source of data: IRENA

Trend in global energy production



Source: Our World in Data based on BP Statistical Review of World Energy (2022) ; Our World in Data based on Ember's Global Electricity Review (2022). ; Our World in Data based on Ember's European Electricity Review (2022).
Note: 'Other renewables' includes biomass and waste, geothermal, wave and tidal.

Net-zero America 2020



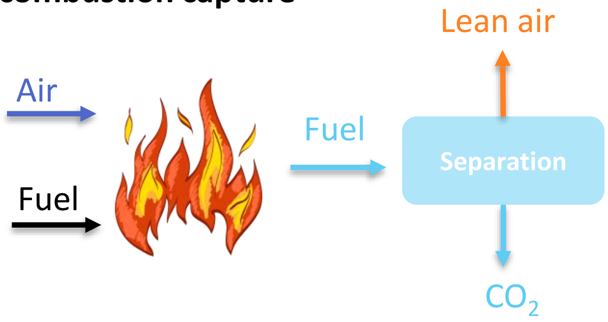
Larson et al. (2021) Net-Zero America: Potential Pathways, Infrastructure and Impacts. Princeton University

2.Introduction to carbon capture and storage (CCS)

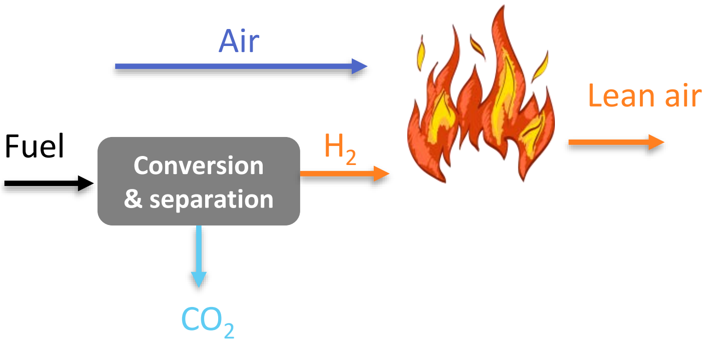
Approaches to CCS

No capture

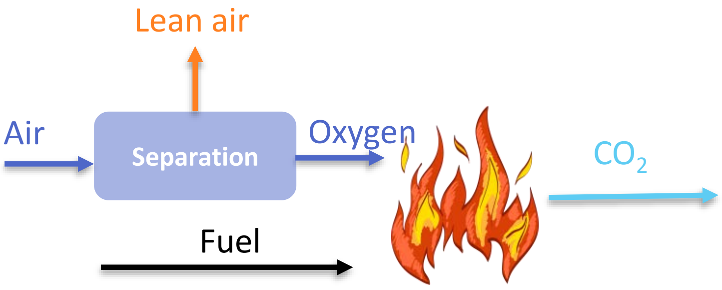
Post-combustion capture



Pre-combustion capture

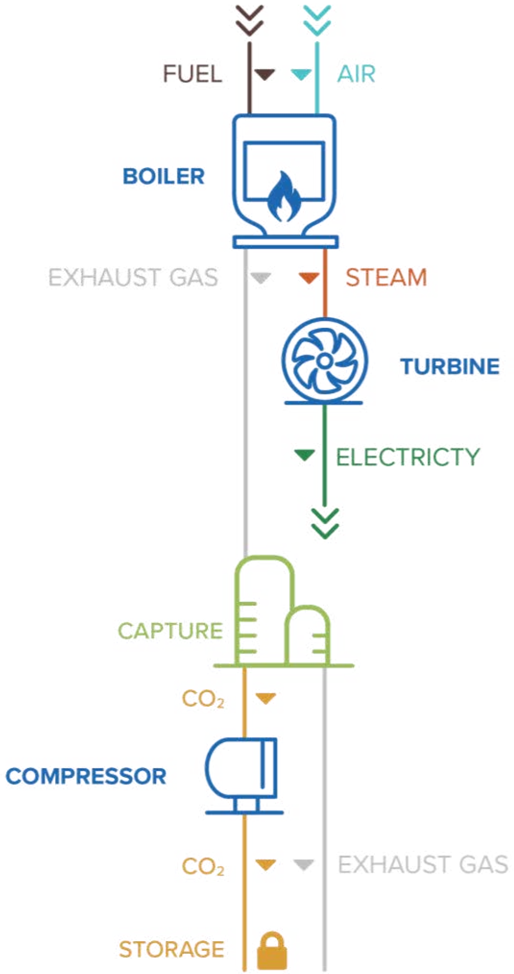


Oxy-fuel combustion



Post-combustion capture

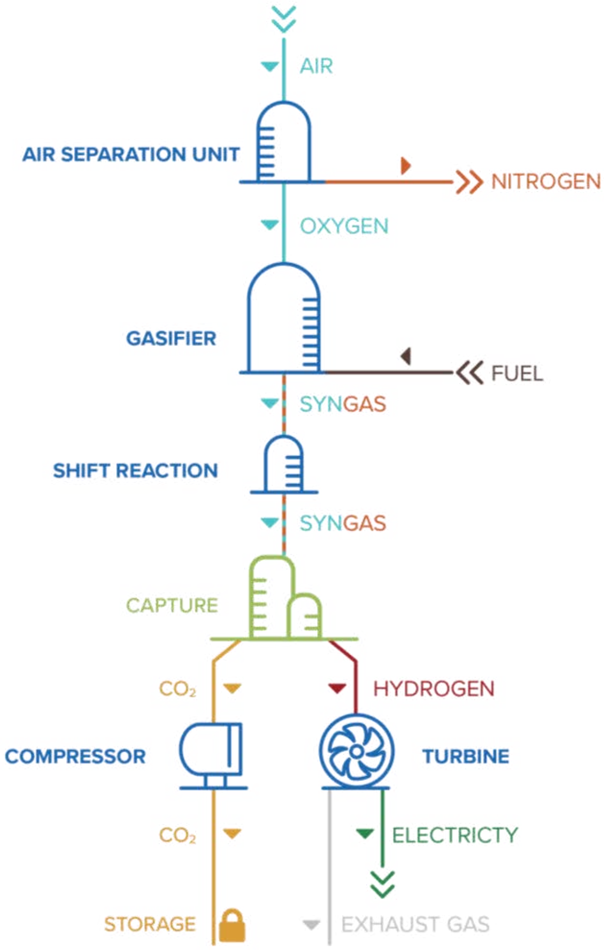
- End-of-pipe technology
- Retrofitting to existing facilities
- Commercially operating



Source of image: Global CCS Institute

Pre-combustion capture

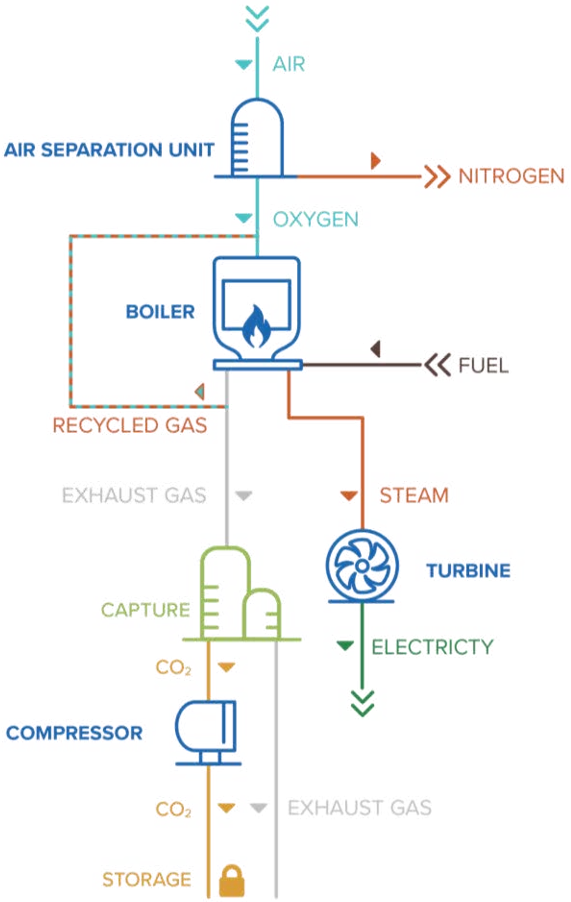
- Energy conversion
- Hydrogen as the energy vector
- Suitable for transportation sector
- Pre-existing technologies
- Require overhaul of existing boilers and turbines



Source of image: Global CCS Institute

Oxy-fuel combustion

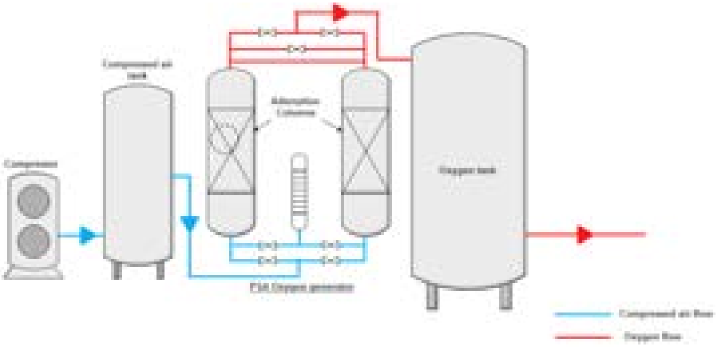
- Combustion in nitrogen-free environment
- Energy penalty associated with air separation
- Recycling CO_2 to regulate flame temperature
- Thermodynamically advantageous when applied for natural gas powerplants



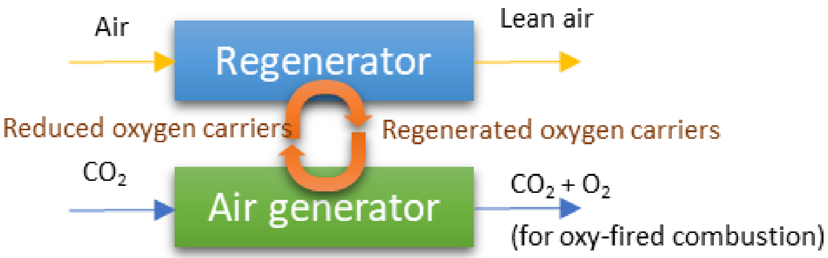
Source of image: Global CCS Institute

In essence, CO_2 capture is gas separation

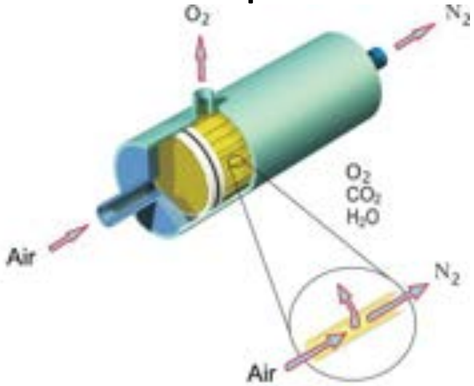
Physisorption



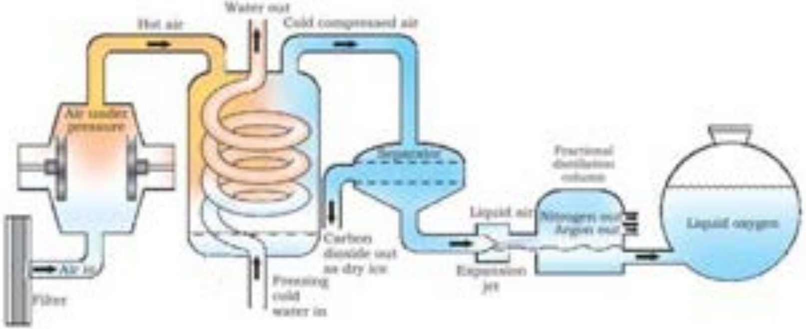
Chemical reaction/adsorption/absorption



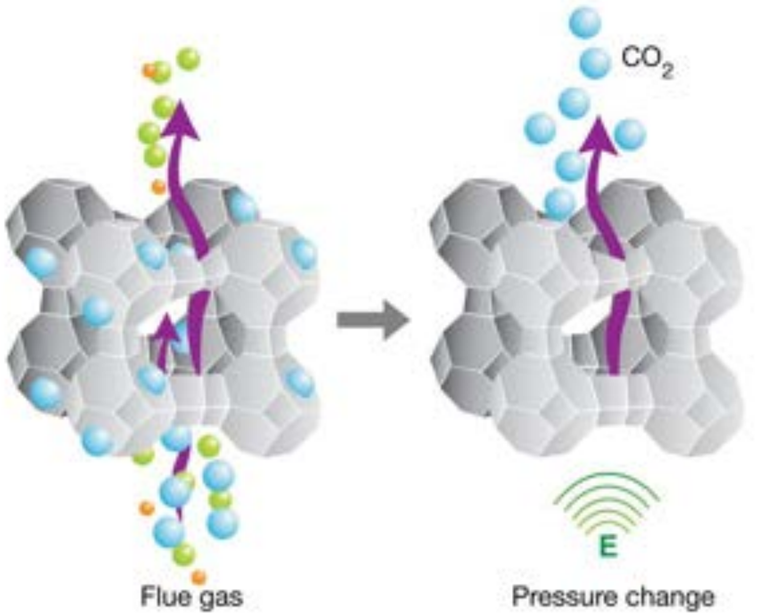
Membrane separation



Distillation



Physisorption

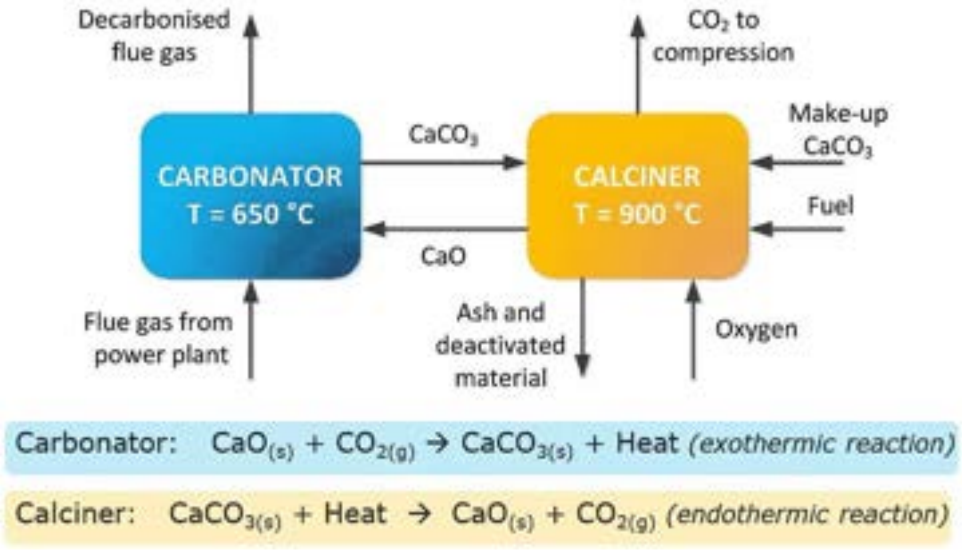


Source of image： CO2CRC

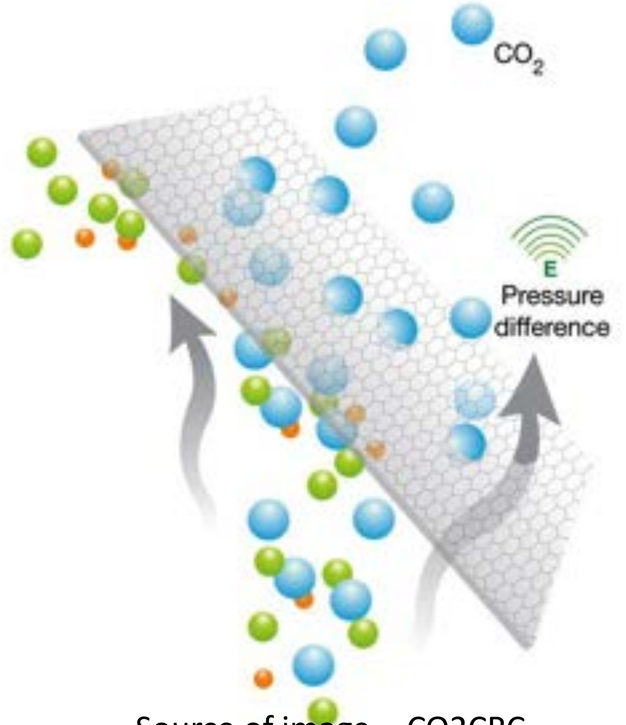
- Physical interaction between gas molecules and sorbents
- Adsorption towers
- Low selectivity
- Pressure swings

Chemical reaction (carbonation) and chemisorption

- Higher selectivity
- Poison by SO_2
- Energy penalty for sorbent regeneration



Membrane separation



Source of image： CO2CRC

- Reverse osmosis
- High selectivity
- Flow flux
- Energy intensive (pressure ratios across the membrane)
- Cost of membranes
- Lifetime of membranes

Air separation (cryogenic distillation)

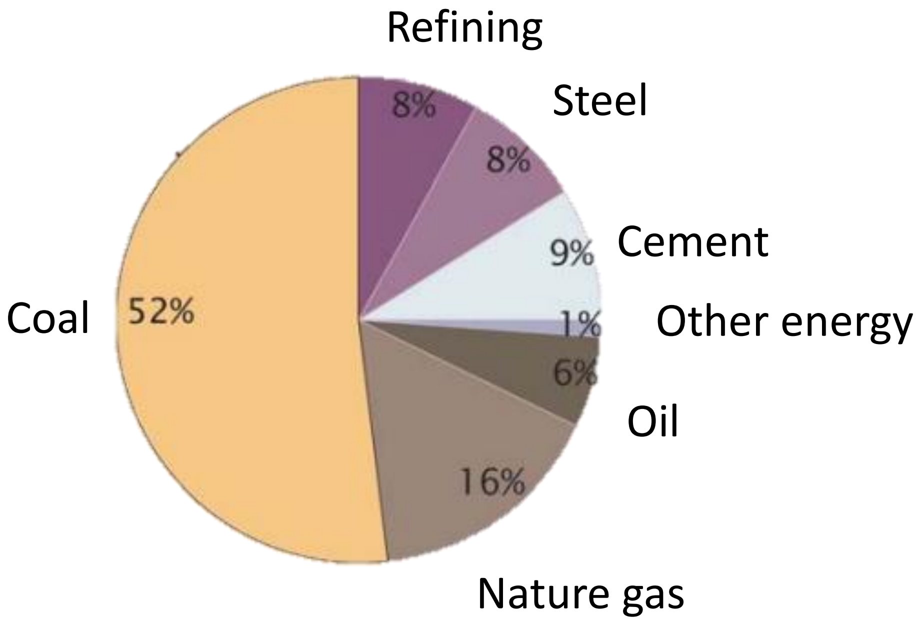
- Cryogenic technology
- Energy intensive
- High CO_2 purity
- Suitable for co-production

Diverse sources of CO_2

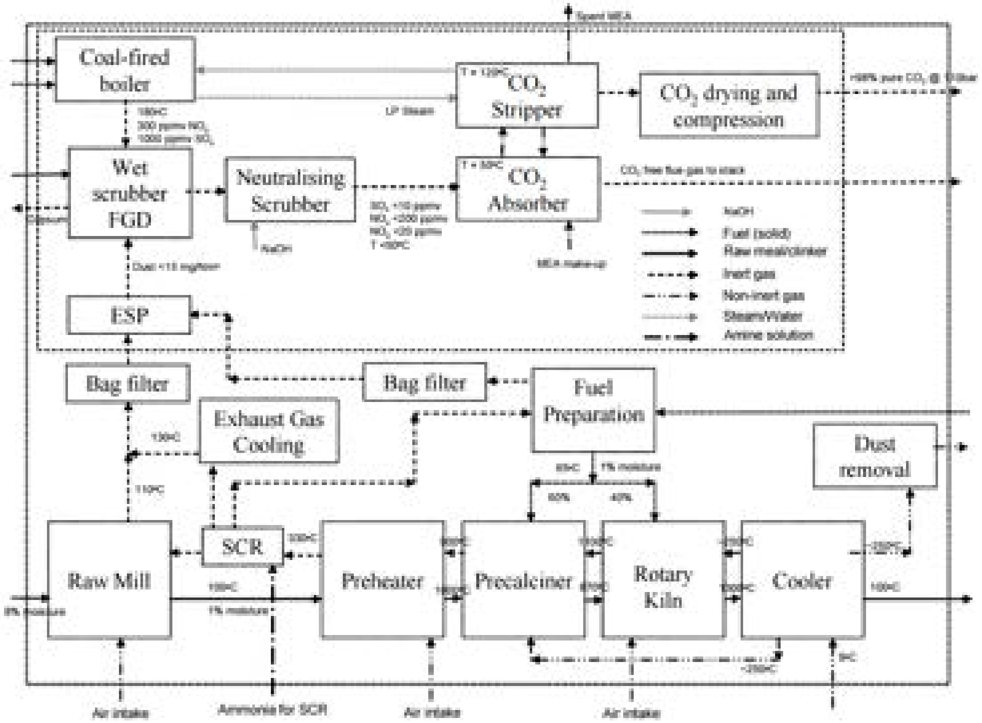
- **Byproduct of the refining**
  - **Oxidative dehydrogenation**
  - **Epoxidation**
  - **Catalytic cracking (catalyst regeneration)**

- **Metallurgy**
  - Carbon
  - Limestone (for slags)

- **Cement industry**
  - Kilns



Application of CCS in cement manufacturing



- Large production volumes
- Inevitable CO_2 generation
- Post-combustion capture
- Oxy-fuel combustion

Energy penalty associated with gas separation

Gibbs free energy of gas mixing (and separation)

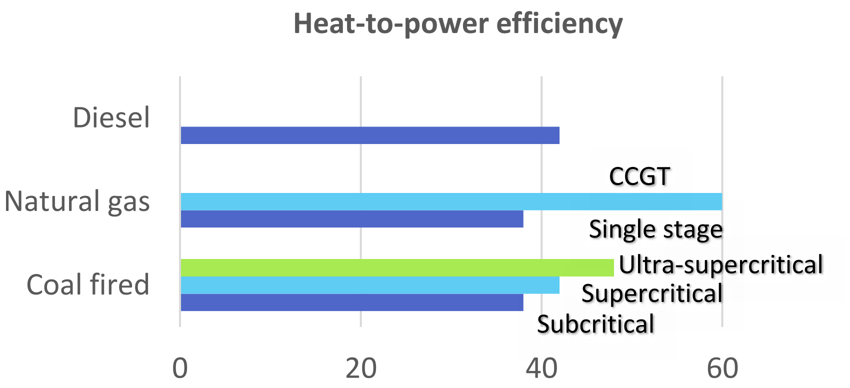
$$\Delta_{mix}G = nTR\sum_i x_i \ln x_i$$

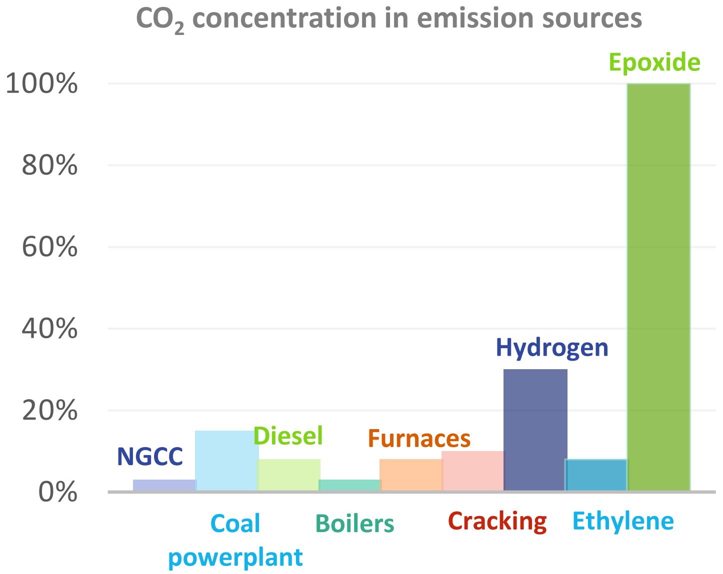
- Separating 1 mole of air (21% O_2 and 78% N_2) requires at least **151 J** of energy.
- Separating CO2 from 1 mole of flue gas requires at least 333 J of energy.
- Actual energy penalty is 2-3 orders of magnitudes higher
- Existing gas separation technologies needs to be more efficient to make CO_2 capture cheaper

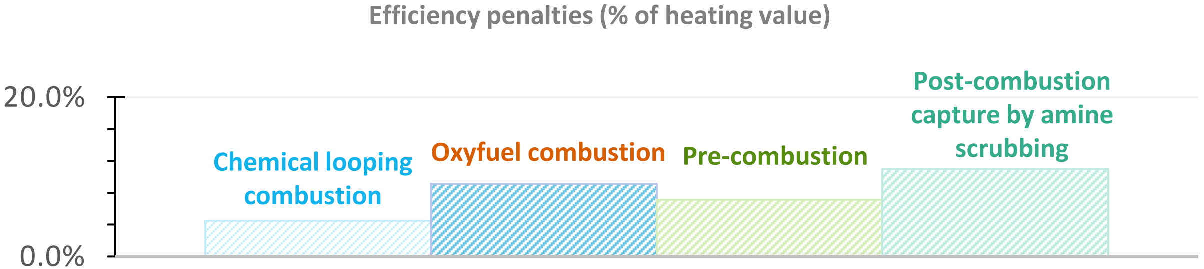
Cost of CO_2 capture

- Energy input for gas separation
- Reduction in powerplant outputs
- Reduction in power generation
- Increment in levelized cost of electricity (e.g. $ per MWh)
- Cost of CO_2 abatement ($ per tonne)
- Cost of CO_2 capture by first generation post-combustion capture facilities (US$100/t-$CO_2$)
- (Estimated) cost of CO_2 capture by next generation post-combustion capture facilities (US$40-60/t-$CO_2$)
- Cost of direct air capture (DAC): US$300-1000/t-$CO_2$.

Powerplant efficiency, CO_2 concentration and efficiency penalties



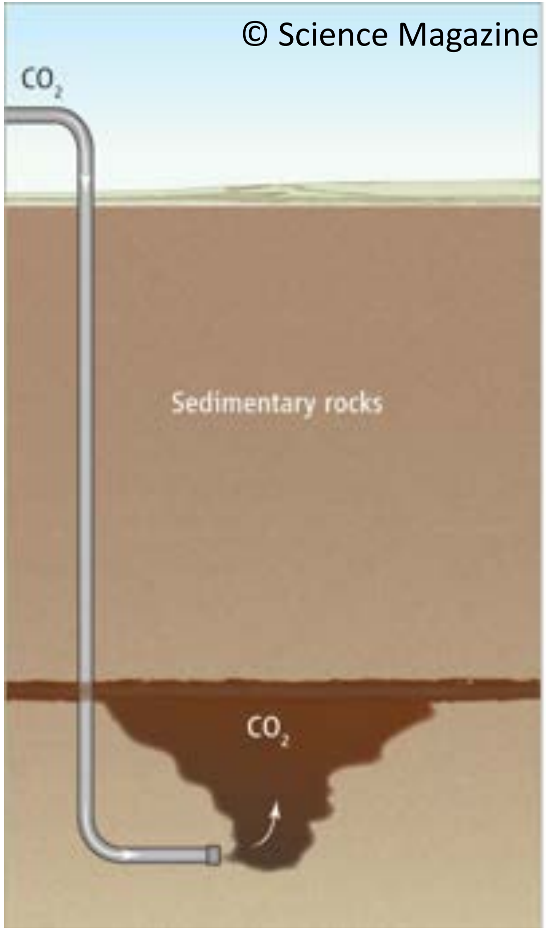




Capital cost

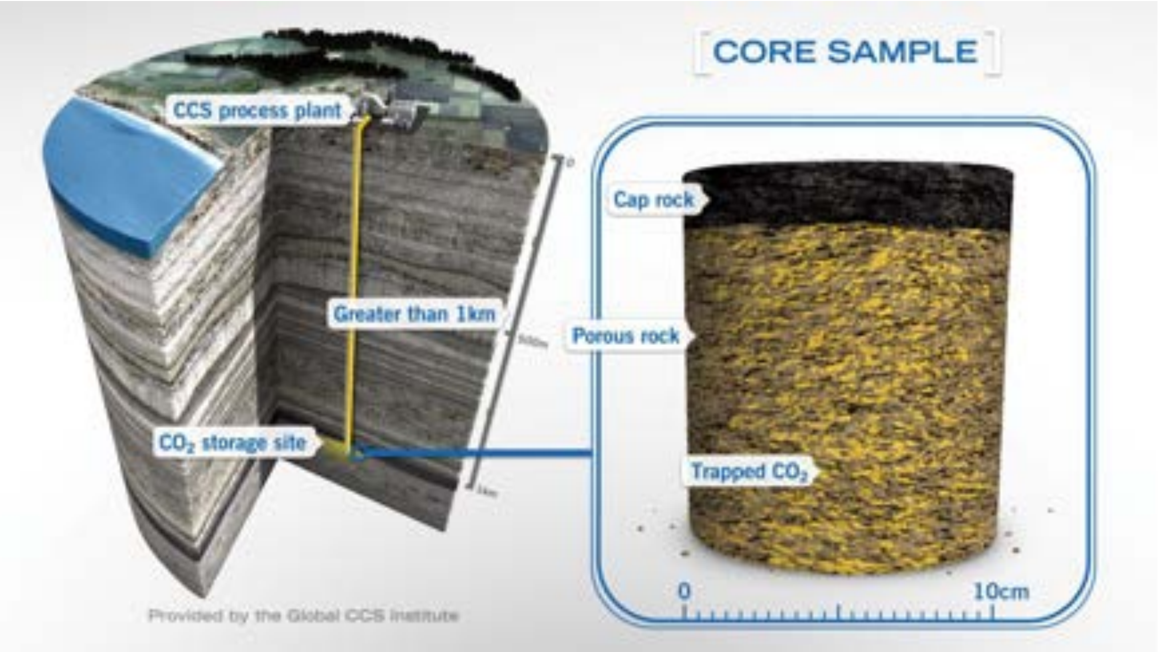
Petra Nova CCS project, started operation from January 2017
Capturing from 33% of flue gas from boiler #8
Producing 99% CO_2 for enhanced oil recovery (EOR)
Total budget: US$1 billion
Stopped operation in 2020 due to low oil price
Operation resumed in Sep 2023

CO_2 storage



CO_2 storage

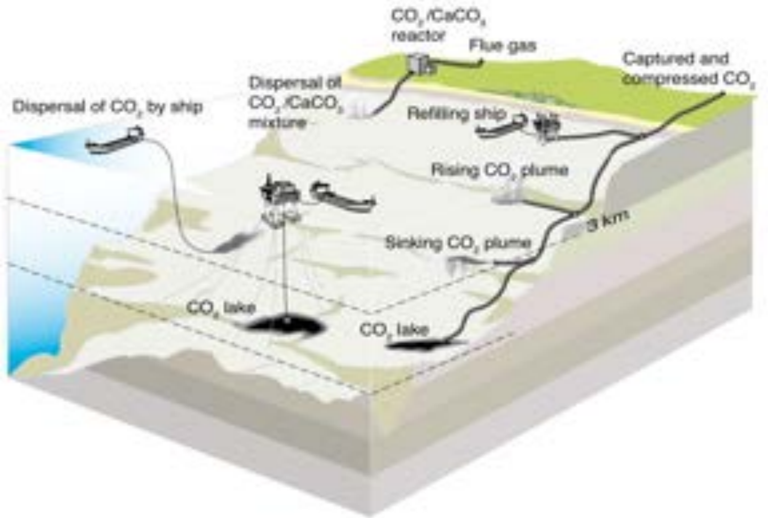
- From fossil fuels to fossil CO2
- Possible pathways
  - Deep sea
  - EOR
  - Geological storage
  - Mineralisation



N.B. For EOR, the net CO_2 emissions vary from about 0.7 to 0.8 tonne CO_2-equivalent per tonne CO_2 stored.

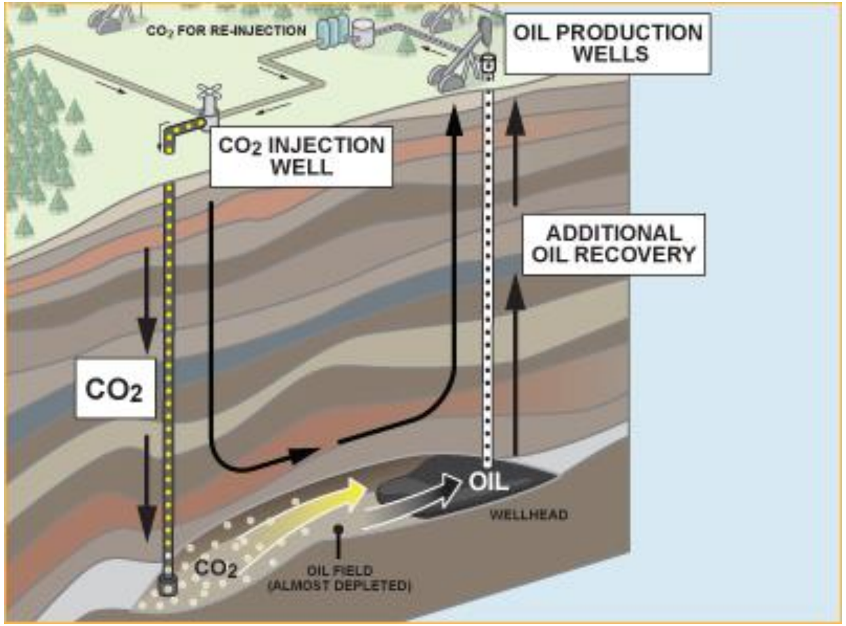
Deep sea storage

- CO_2 is partially soluble in water
- CO_2 hydrates
- Risk of seismic activities
- Abandoned by mainstream research efforts



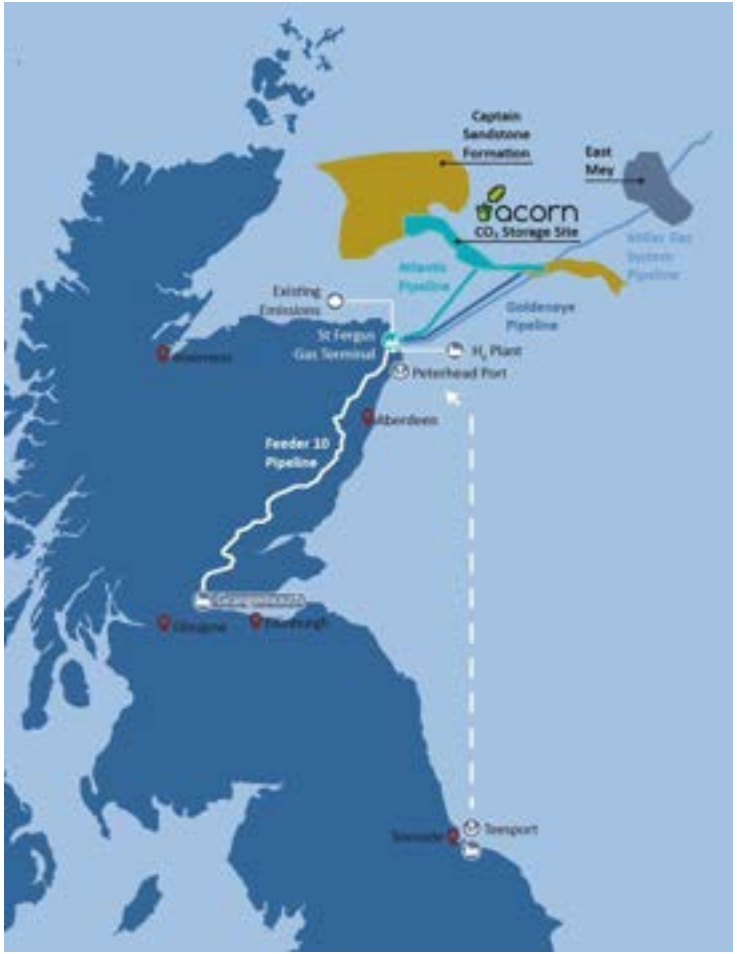
Enhanced oil recovery

- 30 – 60% of the oil reserve cannot be extracted by conventional means
- Economic viability
- The pumping cannot stop
- Potential environmental issues



Enhanced oil recovery

- Suitable for areas with oil and gas fields
- Negative-carbon energy through biomass powerplant + CCS
- International collaboration



Geological storage

- Inject liquid CO_2 to underground cavities, such as oil fields, saline aquafers, abandoned mines, etc.
- Main CCS pathway
- Suitable for seismically inactive areas

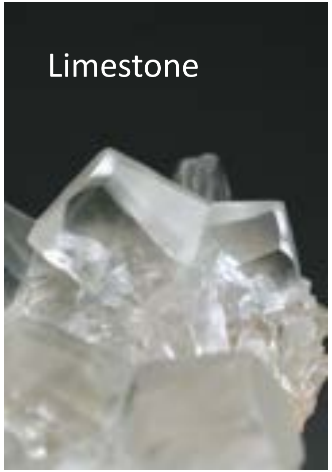
110 MWe CCS project at Boundary Dam, Canada

Williston Basin across the US-Canadian border

CO_2 mineralisation

- 22% of the Earth crust can react with CO_2 to form carbonates
- Thermodynamically feasible
- Extremely slow rate (natural weathering)
- Can be accelerated by industrial processes

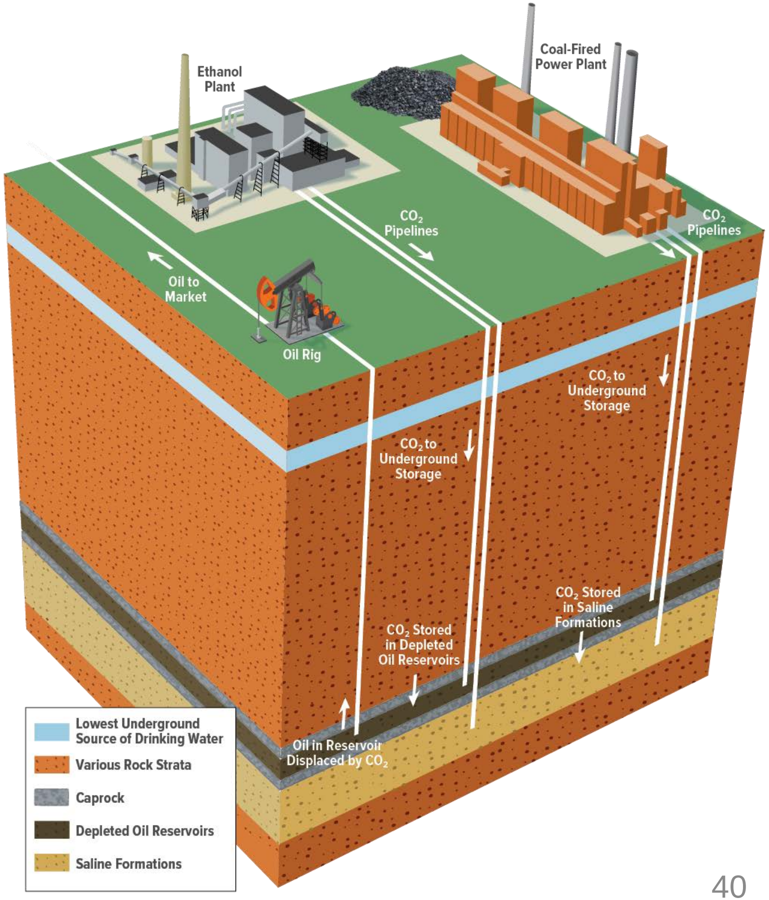
Natural/accelerated weathering →



Cost of CCS

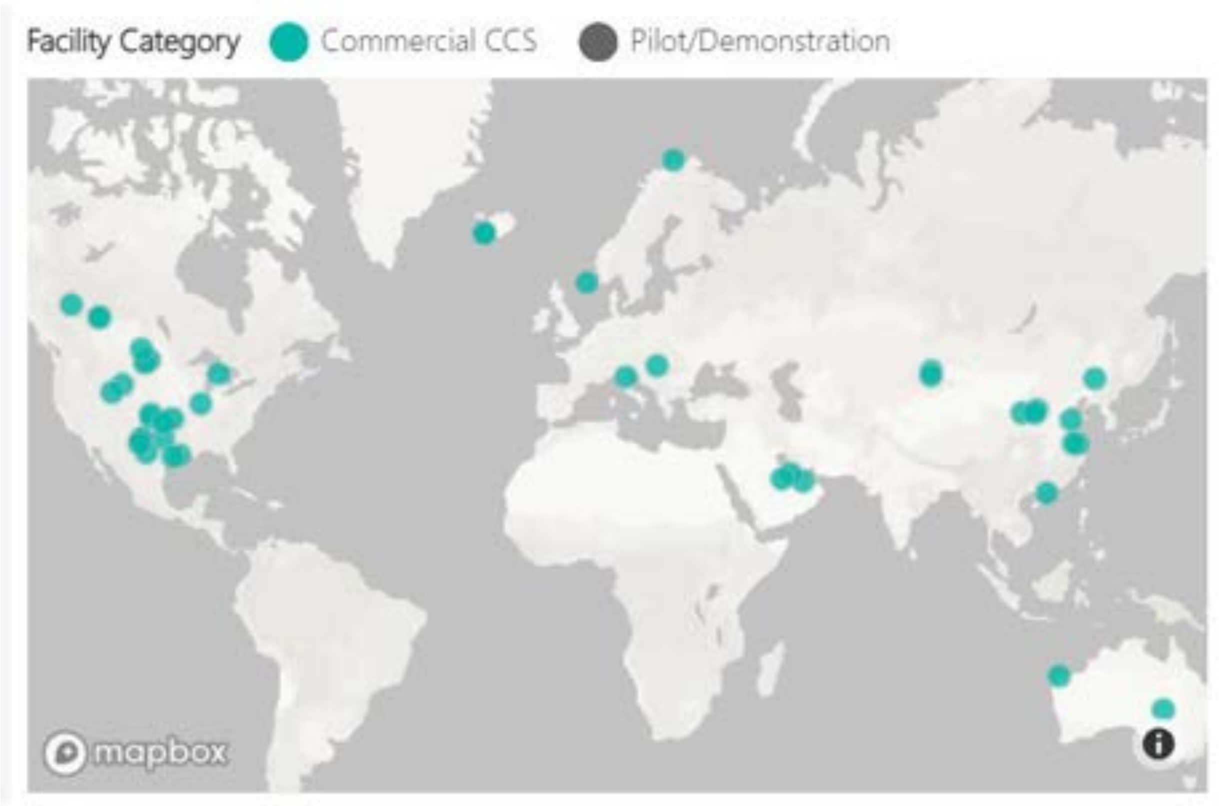
- Capture： USD30.00 – 40.00 /t-CO_2
- Compression： USD10.00 -17.00 /t-CO_2
- Transportation： USD2.00 -10.00 /t-CO_2
- Injection： USD0.50 – 8.00 /t-CO_2
- Monitoring： USD0.10 – 0.30 /t-CO_2
- Total cost is USD60 /t-CO_2

This translates to approximated 6 US cent per kWh

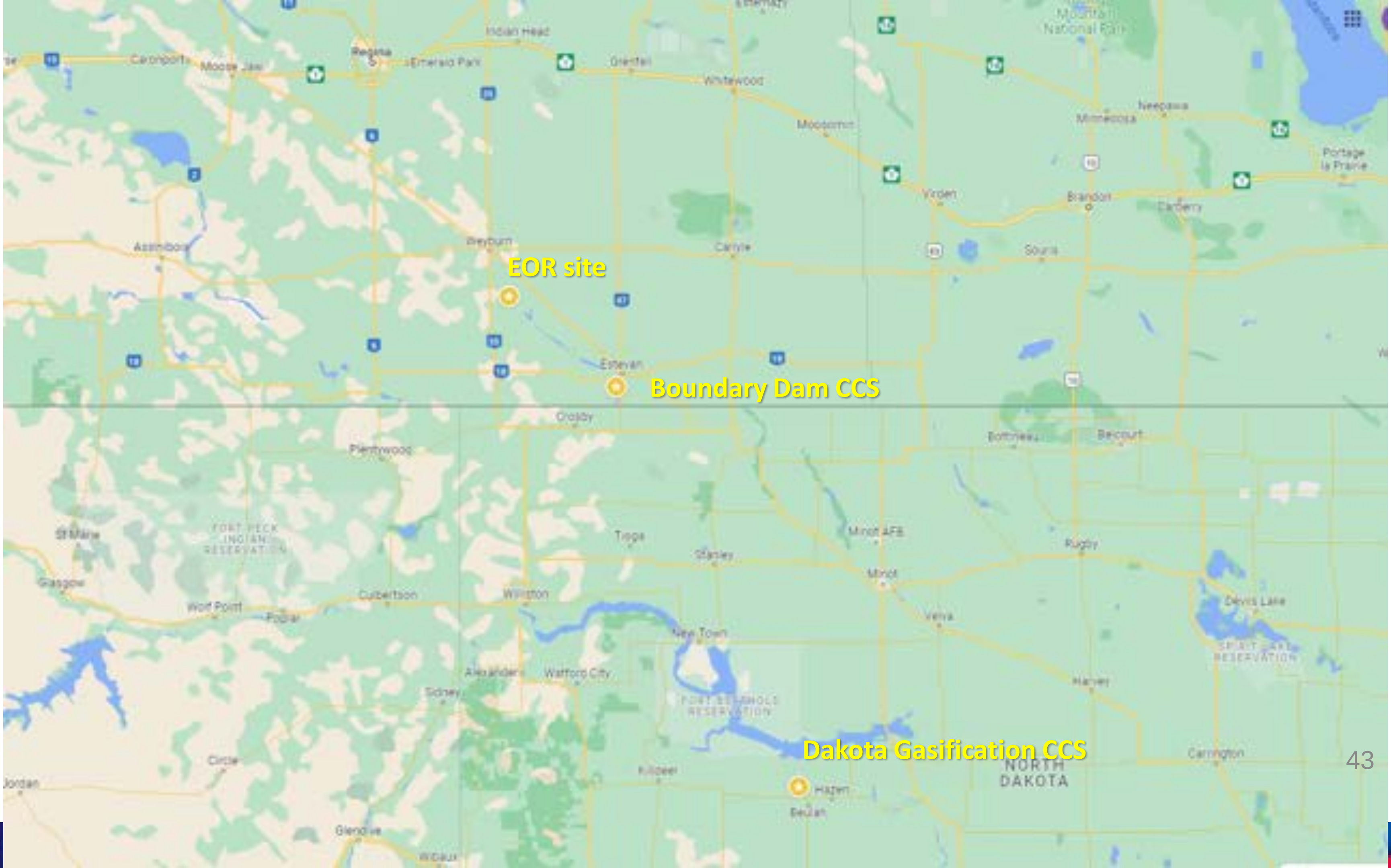


3.Post-combustion CO_2 capture and storage (CCS): case study

Commercially operating CCS plants in the world



https://co2re.co/FacilityData


EOR site
Boundary Dam CCS
Dakota Gasification CCS


COOLING SYSTEM
SaskPower
Boundary Dam
CO2 CAPTURE PLANT
CO2 COMPRESSION FACILITY

SASKATCHEWAN POWER CORPORATION
BOUNDARY DAM
POWER STATION
SaskPower CCS Project
August 28, 2014
Thank you to the 1,700 SaskPower workers and contractors, who contributed to building the world's first post-combustion carbon capture project on a coal-fired plant. And a special thank you to the employees of Boundary Dam Power Station and their families for their hard work and sacrifice.
The project represents more than 4.5 million man-hours of work, without a single time-lost injury.
Your dedication makes SaskPower a world leader in sustainable power.
Thank you also to our many business partners and subcontractors that have helped make this project a reality.
SaskPower
Powering the future

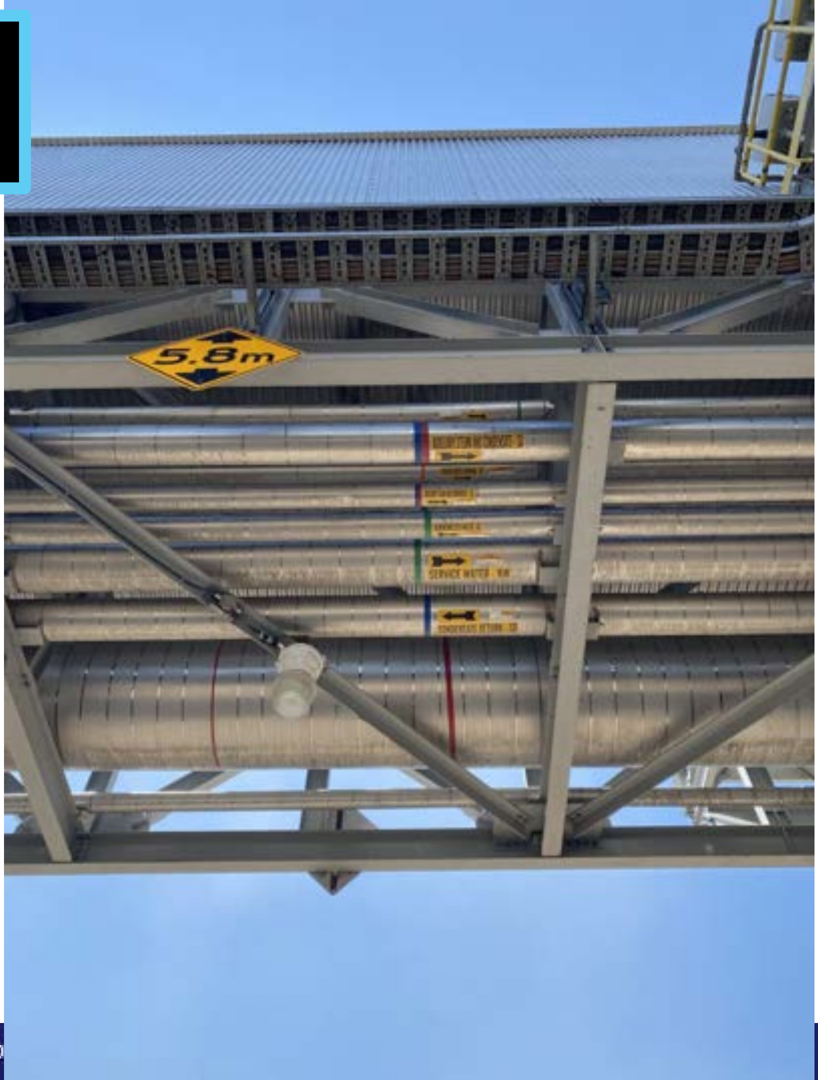

4F
FEEDER

Steam turbine
Unit 6

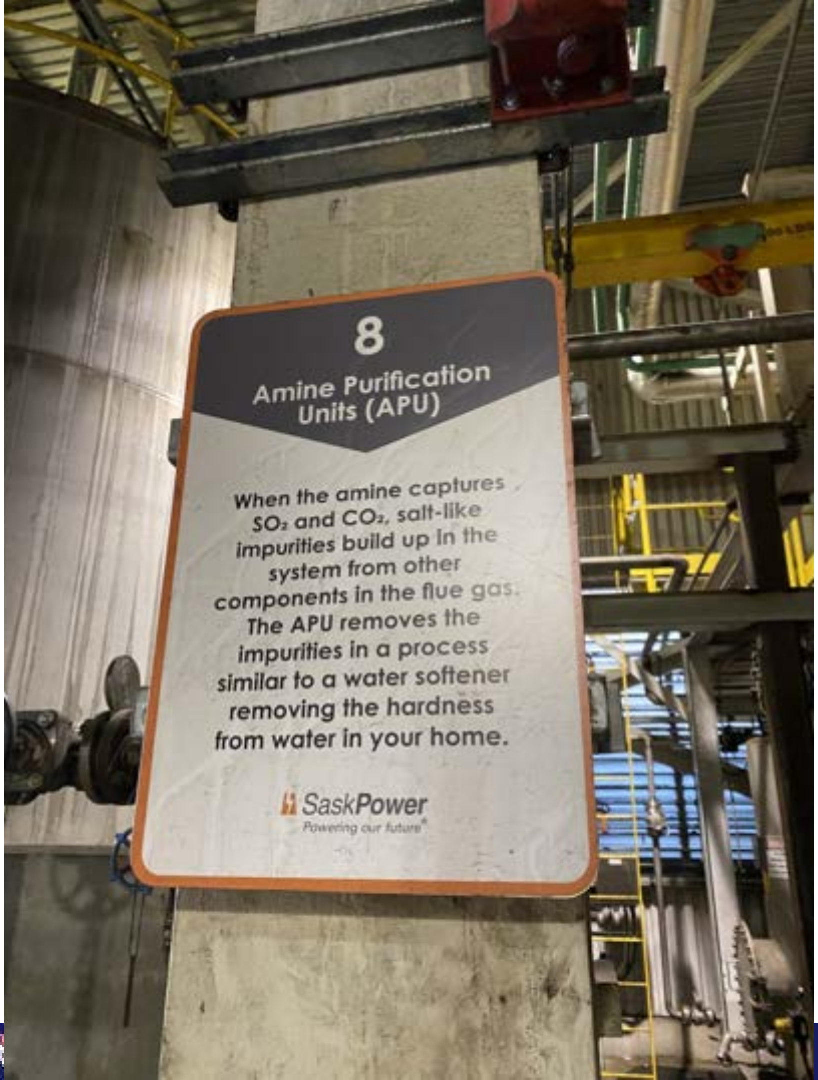

HITACHI
HITACHI STEAM TURBINE
TYPE TCDF-33.5 REHEAT CONDENSING
RATING 322,740 kW SPEED 3,600 rpm
STAGES 16 MAIN STEAM PRESS. 1814 psia
MAIN STEAM TEMP. 1000 °F REHEAT STEAM TEMP. 1000 °F
EXHAUST PRESS. 1.6 inHgabs MFG. NO. K19N772
DATE 2010 INSTRUCTION TS-1160417-1
Hitachi, Ltd. Tokyo Japan
310RC09-850-1


HITACHI
HYDROGEN / WATER COOLED GENERATOR
TYPE TFLQQ
FORM KD
HYDROGEN PRESS. 0.31 MPa
PHASES 3
POLES 2
CAPACITY 360000 kVA
POWER FACTOR 0.90
OUTPUT 324000 kW
SPEED 3600 min⁻¹
FREQUENCY 60 Hz
VOLTAGE 18000 V
CURRENT 11547 A
EXCITATION VOLTAGE 375 V
FIELD CURRENT 3183 A
CODE ANSI C50.10-1990 ANSI C50.13-1989
INSULATION CLASS B
MFG. No. ROTOR 16H102-1 (REPLACE) STATOR 16M254-1 (REPLACE)
MFG. YEAR ROTOR 2010 (REPLACE) STATOR 2002 (REPLACE)
Hitachi, Ltd. Tokyo Japan
310RC11-652-1

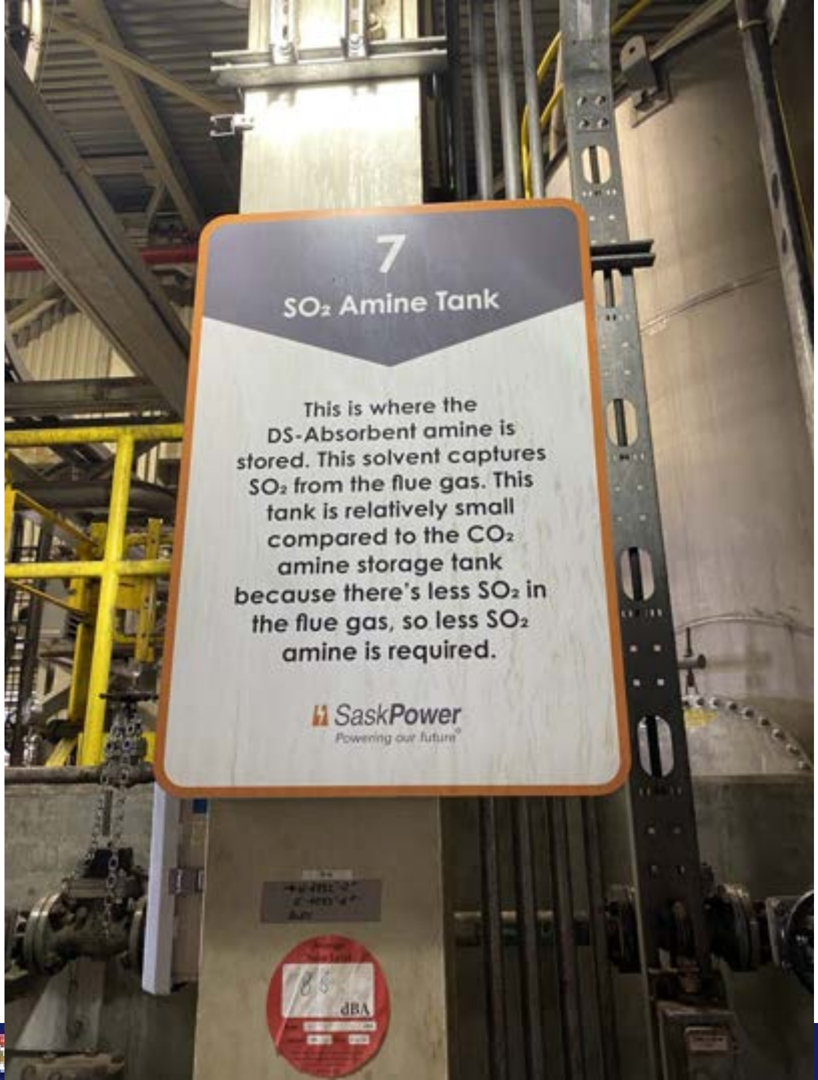
Cooling water, hot water, steam, flue gas

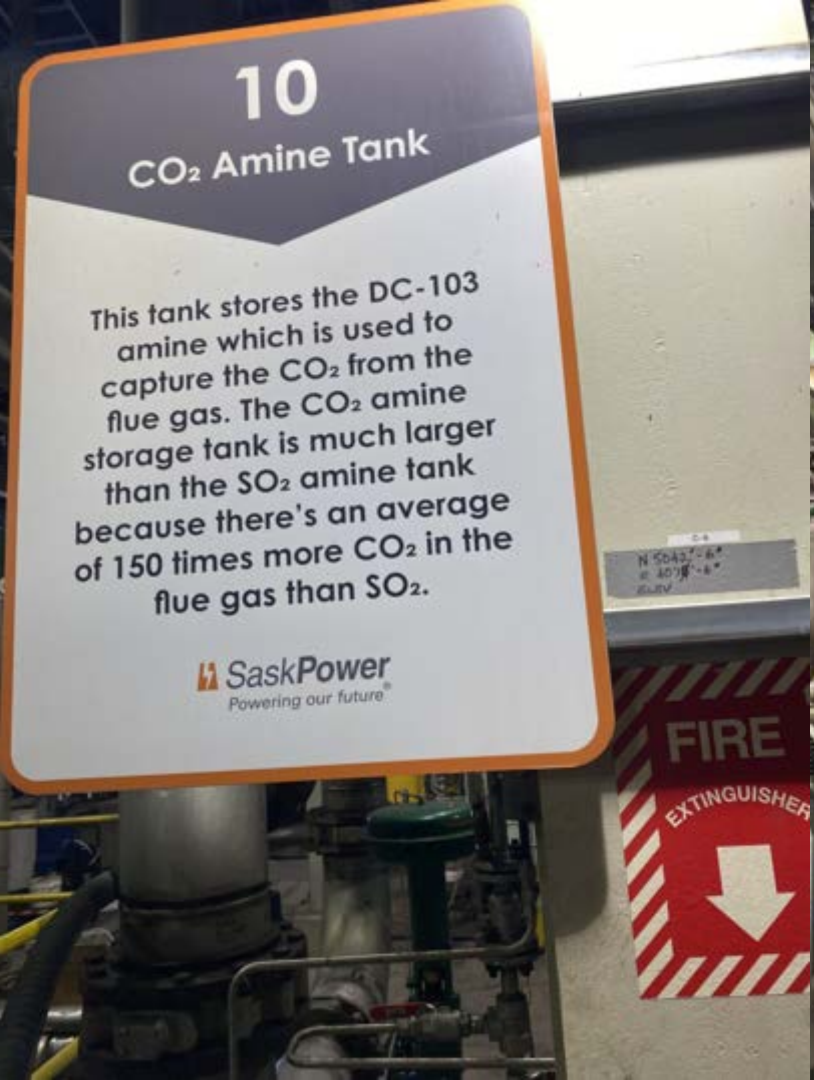


Amine scrubbing towers


8
Amine Purification Units (APU)
When the amine captures SO_2 and CO_2, salt-like impurities build up in the system from other components in the flue gas. The APU removes the impurities in a process similar to a water softener removing the hardness from water in your home.
SaskPower
Powering our future

IRON REMOVAL
TWR-470


7
SO₂ Amine Tank
This is where the DS-Absorbent amine is stored. This solvent captures SO₂ from the flue gas. This tank is relatively small compared to the CO₂ amine storage tank because there's less SO₂ in the flue gas, so less SO₂ amine is required.
SaskPower
Powering our future
dBA


10
CO_2 Amine Tank
This tank stores the DC-103 amine which is used to capture the CO_2 from the flue gas. The CO_2 amine storage tank is much larger than the SO_2 amine tank because there's an average of 150 times more CO_2 in the flue gas than SO_2.
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Powering our future
FIRE
EXTINGUISHER

8 stage CO_2 compression plant (4 wet stages and 4 dry stages). Power consumption: 13.6 MW

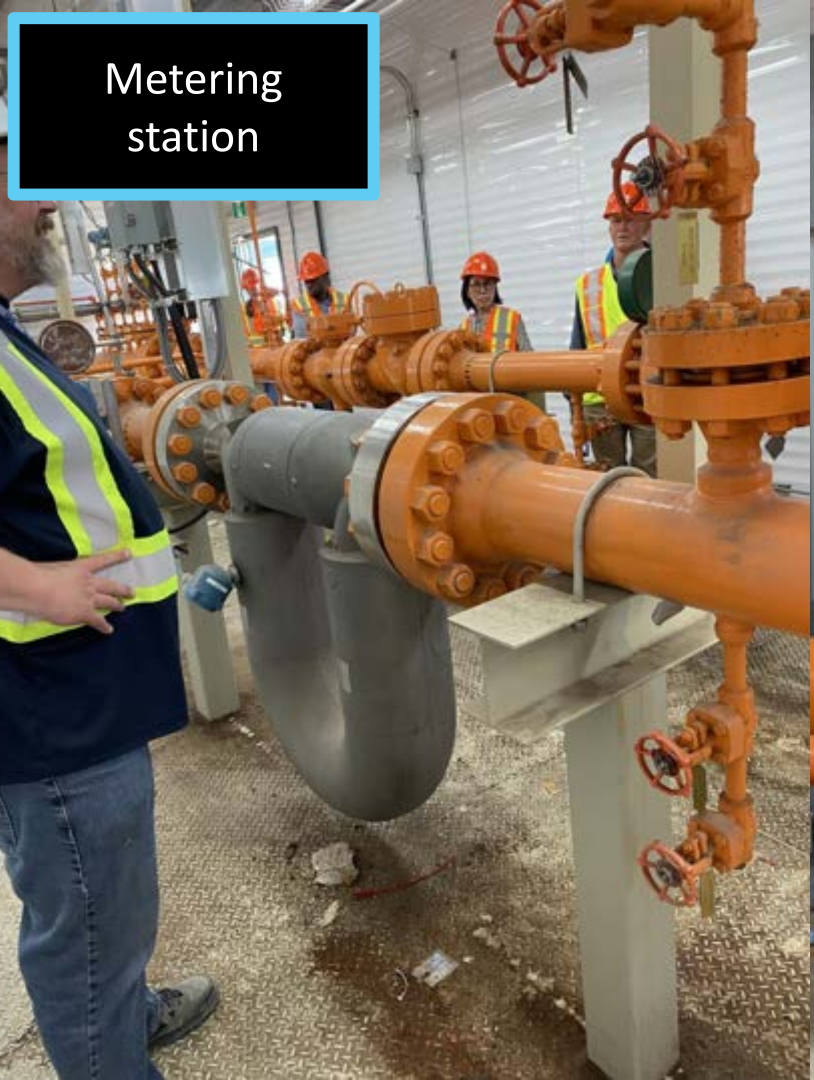
Pipeline for compressed CO_2

Experimental site for CO_2 injection

Injection point

Pressure monitoring by nitrogen

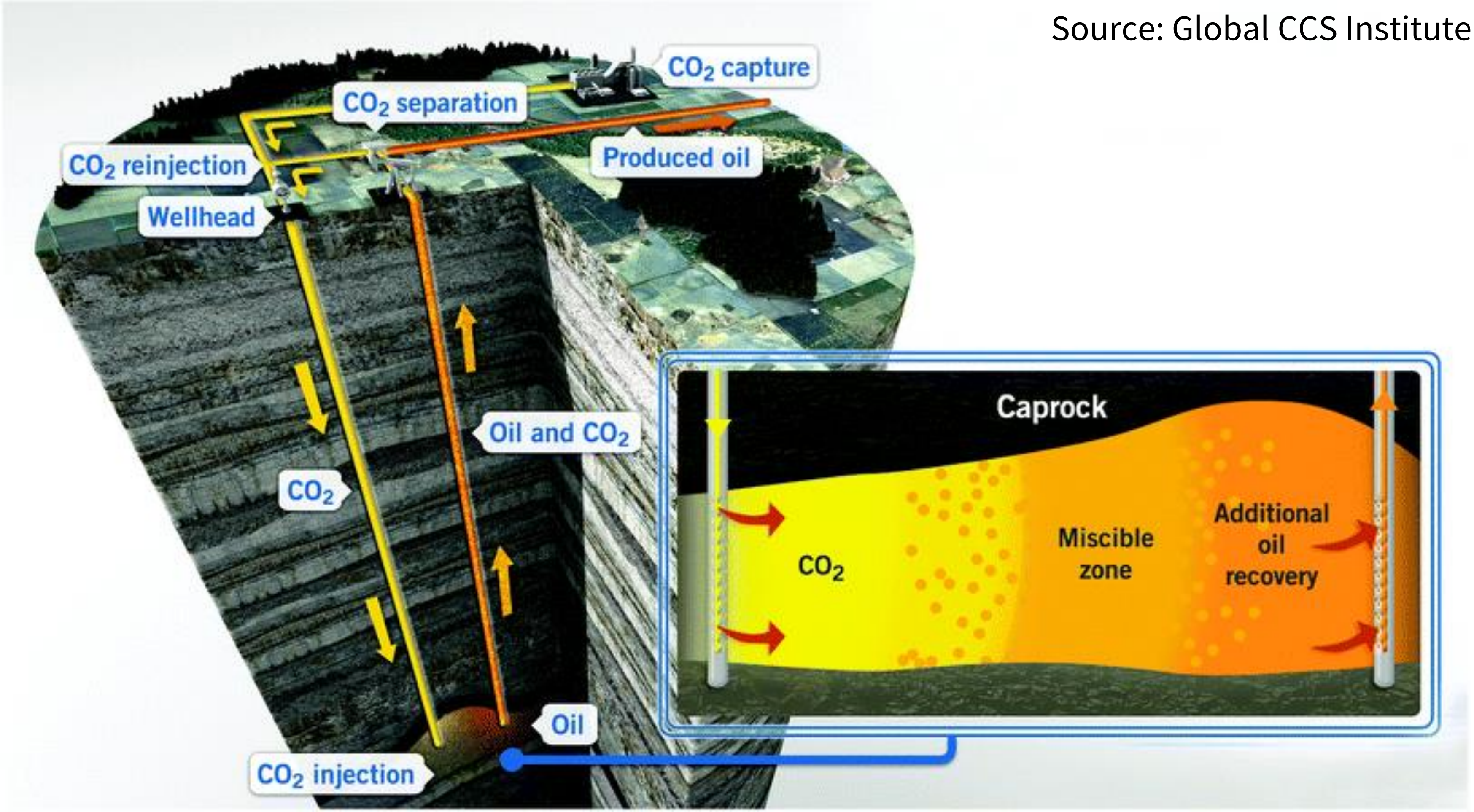
Metering station



EOR field

CO$_2$ metering station for EOR

Source: Global CCS Institute



Water-oil separation post-EOR

Oil pipeline for EOR

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4. Challenges for CCS technologies

Failure cases

- Mongstad Project, Norway. Abandoned in 2013 after several billions of USD of expenditure.
- BP DF-1 project; regarded as economically unviable, Funding withdrawn.
- Kemper Country, Mississippi, US. Delay, exceeded budget, technical issues.
- And many more.

Possible reasons to failure

First generation CCS technologies are almost all first-of-it- kind.

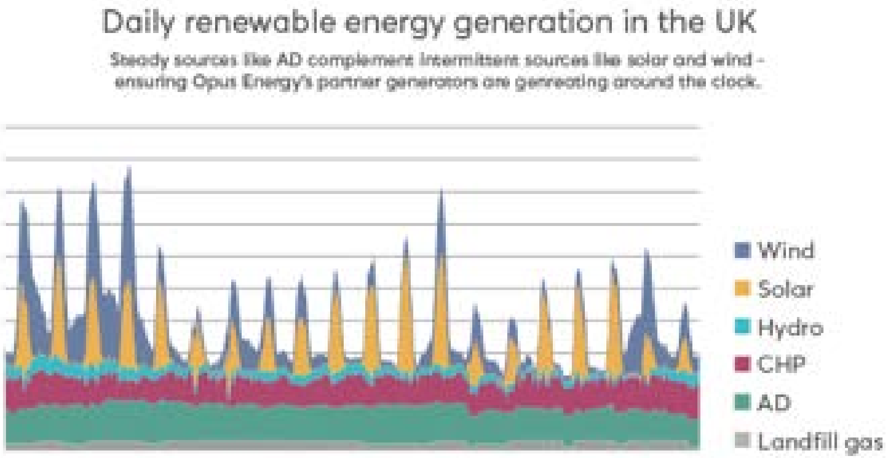
- Funding mechanisms
- Lack of know-hows
- Lack of viable business models
- Lack of economy of scale

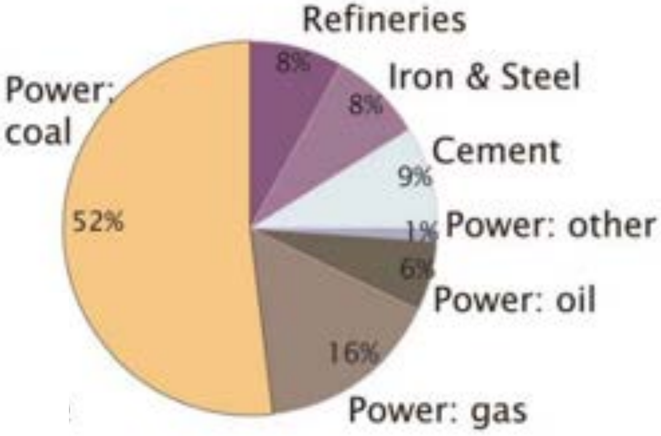
Voices of skepticism

- CCS is a transitional solution and an unnecessary distraction from developing renewable energies
- CCS technology is not mature
- CCS technology is too expensive

“CCS is a transitional solution”

- Conventional (fossil-fuel powered) thermal powerplants are still required to provide a stable baseload to our electricity grid.
- CCS technology can address industrial emissions from non-power sectors

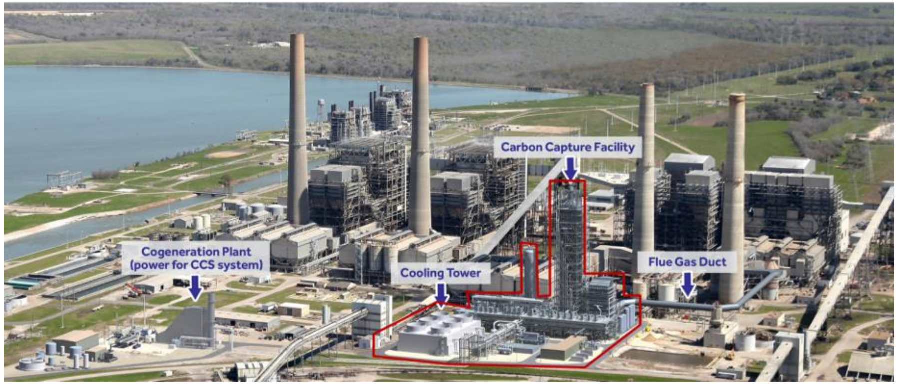




“CCS technology is not mature”

- Both CCS and CCU technologies have been demonstrated at commercial scales

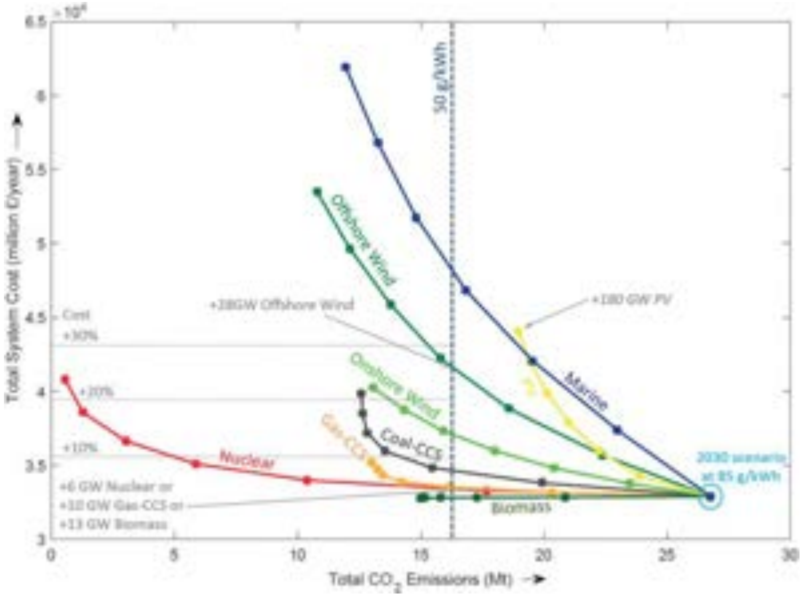
Petra Nova CCS project could provide 200 MW of low carbon electricity



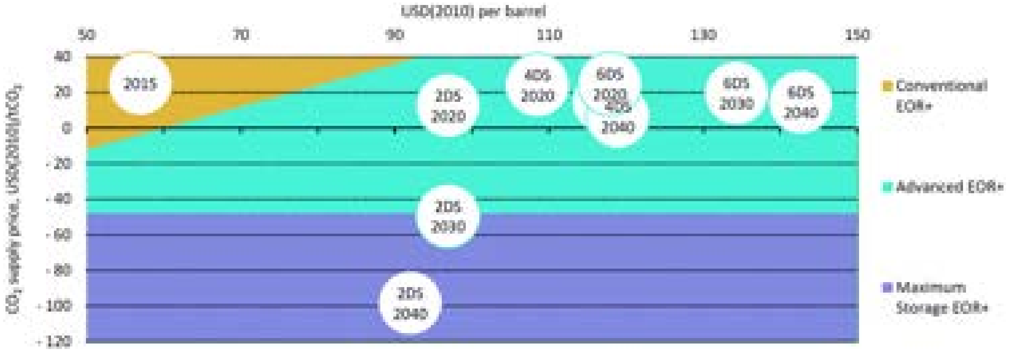
1000 t/year solar powered CO_2 to methanol project, Lanzhou, China

“CO_2 technologies are too expensive”

When deployed at a global scale, CCS-powerplants offers much cheaper low-carbon electricity than renewables.



The cost impact of CCS is less than the impact of fluctuation of oil price.



Energy Environ. Sci., 2018, 11, 1062-1176

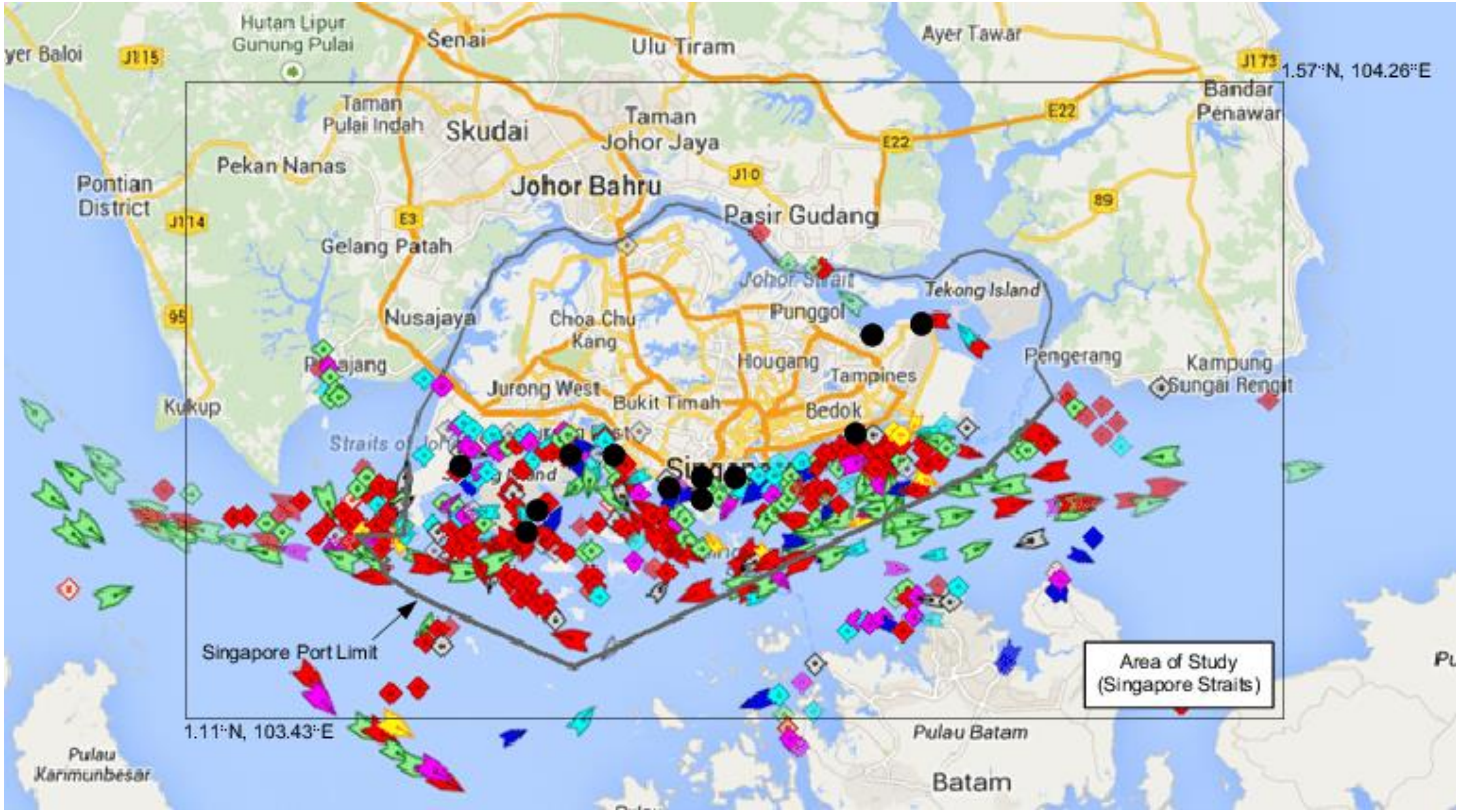
CCS is not a competitor of renewables. They are scaled up differently.

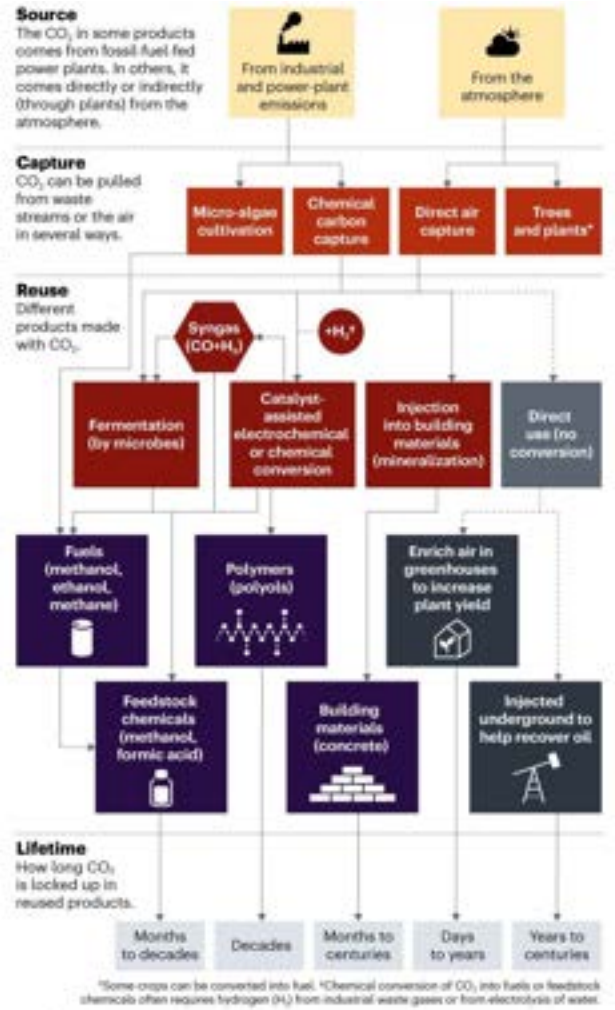
VS

- CCS sounds less green than renewables
- End-of-pipe technology sounds less attractive than no emission

5. Future opportunities -CO_2 capture & utilization (CCU)

CCS is not suitable for all countries





CO_2 capture, storage and utilization (CCSU)

Direct use: F&B, semiconductor, building, niche applications

Biological: greenhouses, algae cultivation

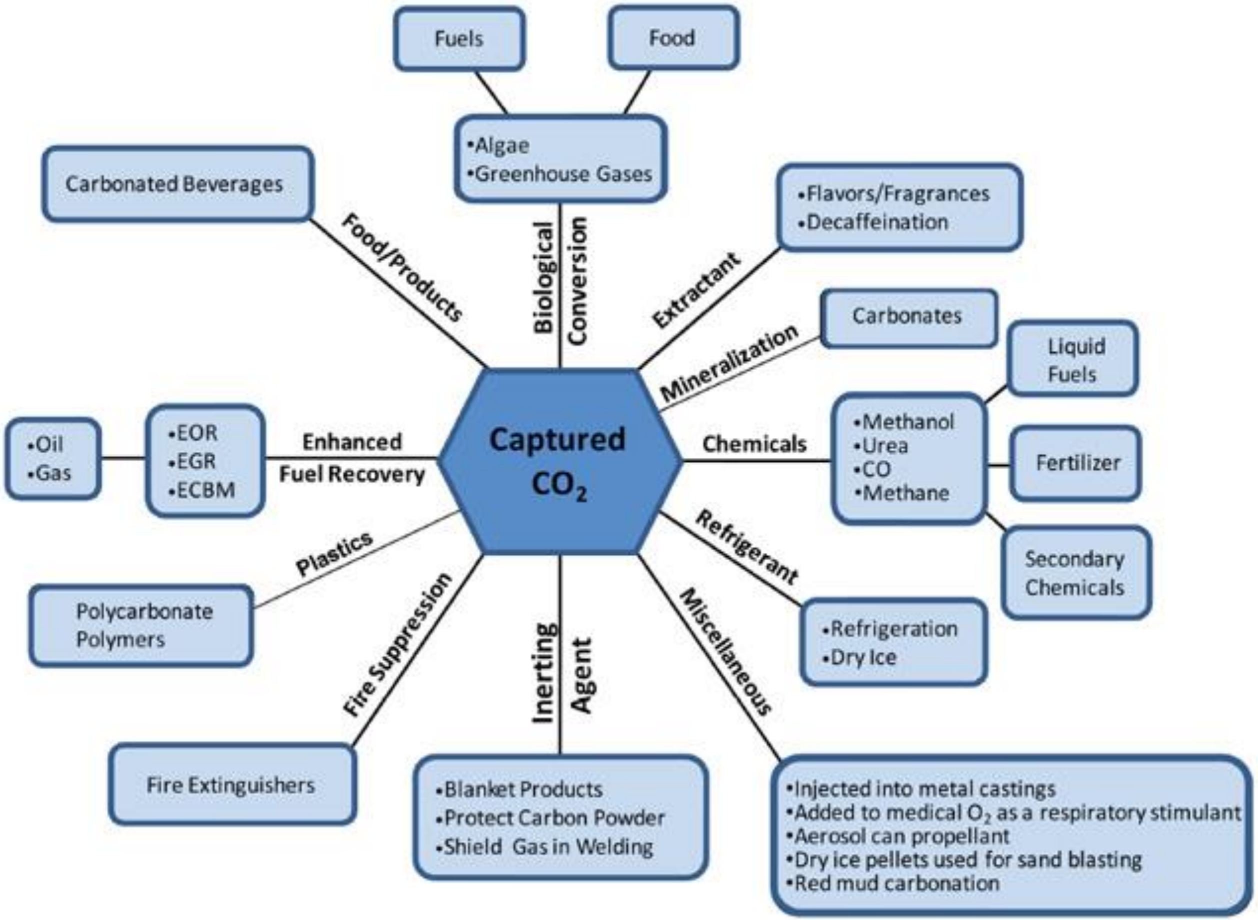
Carbonation: mineralization, cement curing

Chemicals: polycarbonate, bicarbonate

Oil production: EOR

Chemical conversion: CO_2 hydrogenation to syngas, olefins, alcohols, etc.

Nature **603**, 780-783 (2022)
doi: https://doi.org/10.1038/d41586-022-00807-y


Fuels
Food
•Algae
•Greenhouse Gases
Carbonated Beverages
•Flavors/Fragrances
•Decaffeination
Food/Products
Biological Conversion
Extractant
Carbonates
Mineralization
Liquid Fuels
•Oil
•Gas
•EOR
•EGR
•ECBM
Enhanced Fuel Recovery
Captured CO_2
Chemicals
•Methanol
•Urea
•CO
•Methane
Fertilizer
Plastics
Refrigerant
Secondary Chemicals
Polycarbonate Polymers
Fire Suppression
Inerting Agent
Miscellaneous
•Refrigeration
•Dry Ice
Fire Extinguishers
•Blanket Products
•Protect Carbon Powder
•Shield Gas in Welding
•Injected into metal castings
•Added to medical O_2 as a respiratory stimulant
•Aerosol can propellant
•Dry ice pellets used for sand blasting
•Red mud carbonation

Technological challenge

Energy consumption

Direct use

Fire extinguishers
Supercritical CO_2
Agricultural stimulant
Dry ice
Blanketing gas
Respiration stimulant

Carbonation

Fizzy drinks
Bicarbonate
Polycarbonate
Cement curing
Carbon aggregates
Urea

Direct hydrogenation

Methane
Methanol
Formic acid
Formaldehyde
Ethanol
Dimethyl ether

Hydrogenation via CO

Methane
Methanol
Formaldehyde
Ethanol
Ethylene
Aviation fuels

CO_2 hydrogenation

- C1 conversion:

  $CO_2 + H_2 = CO + H_2O$

  $CO_2 + 4H_2 = CH_4 + 2H_2O$

- Carboxylic acid

  $CO_2 + H_2 = HCOOH$ (Formic acid)

  $CO_2 + 2H_2 = ½\ CH_3COOH + H_2O$ (Acetic acid)

  $CO_2 + 7/3H_2 = 1/3\ C_2H_5COOH + 4/3H_2O$ (Propanoic acid)

- Aldehydes

  $CO_2 + 2H_2 = HCHO + H_2O$ (Formaldehyde)

  $CO_2 + 5/2H_2 = 1/2CH_3CHO + 3/2H_2O$ (Acetaldehyde)

  $CO_2 + 8/3H_2 = 1/3C_2H_5CHO + 5/3H_2O$ (Propanol)

- Alcohols

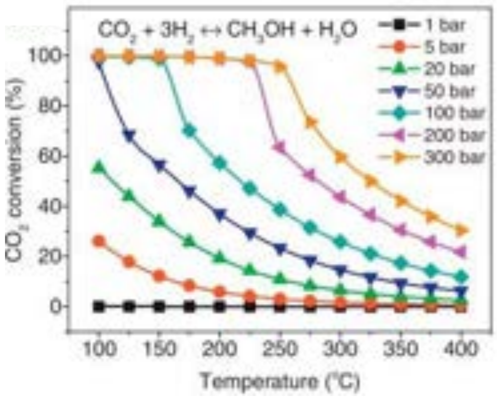
  $CO_2 + 3H_2 = CH_3OH + H_2O$ (Methanol)

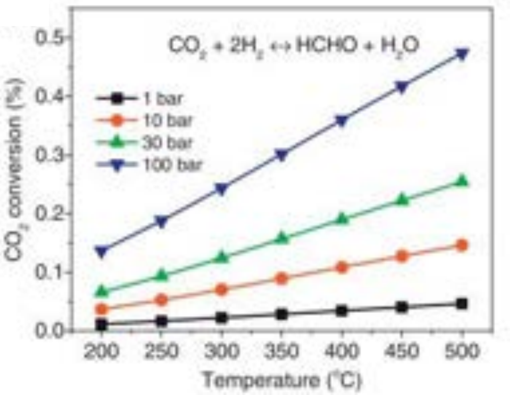
  $CO_2 + 3H_2 = 1/2C_2H_5OH + 3/2H_2O$ (Ethanol)

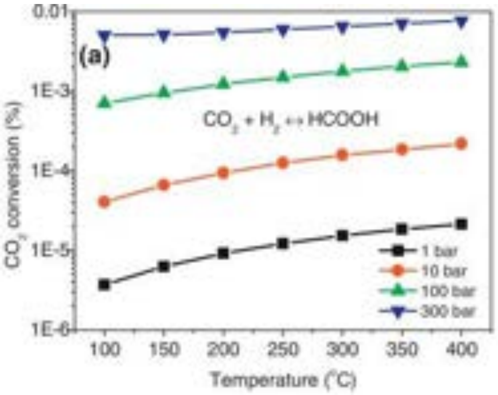
  $CO_2 + 3H_2 = 1/3C_3H_7OH + 5/3H_2O$ (Propanol)

CO_2 hydrogenation - thermodynamics

- Many CO2 hydrogenation reactions are limited by thermodynamic equilibrium
- Low comversion = high recycling ratio = high energy penalty
- High boiling point products favour high pressures





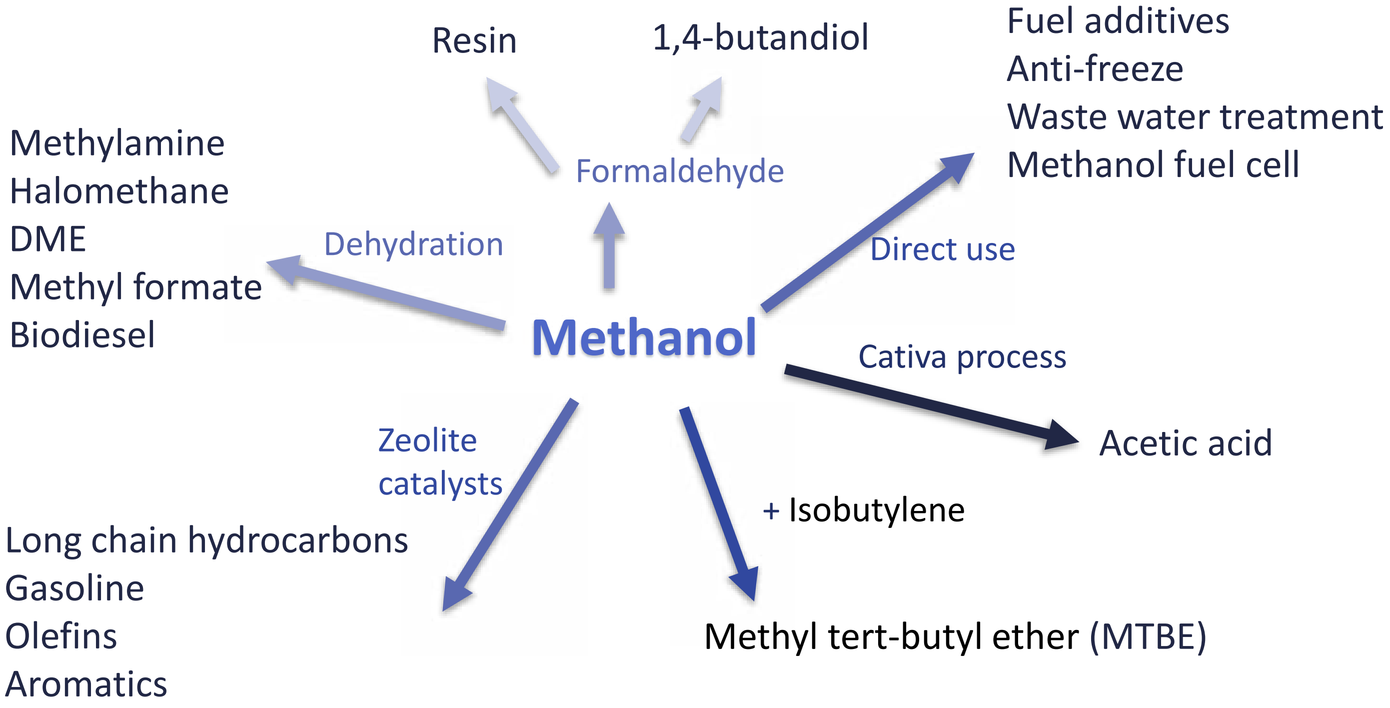


Jia et al. *Journal of Energy Chemistry* 25, 2016: 1027–37.

The cost of CO_2 hydrogenation is dominated by the cost of green hydrogen

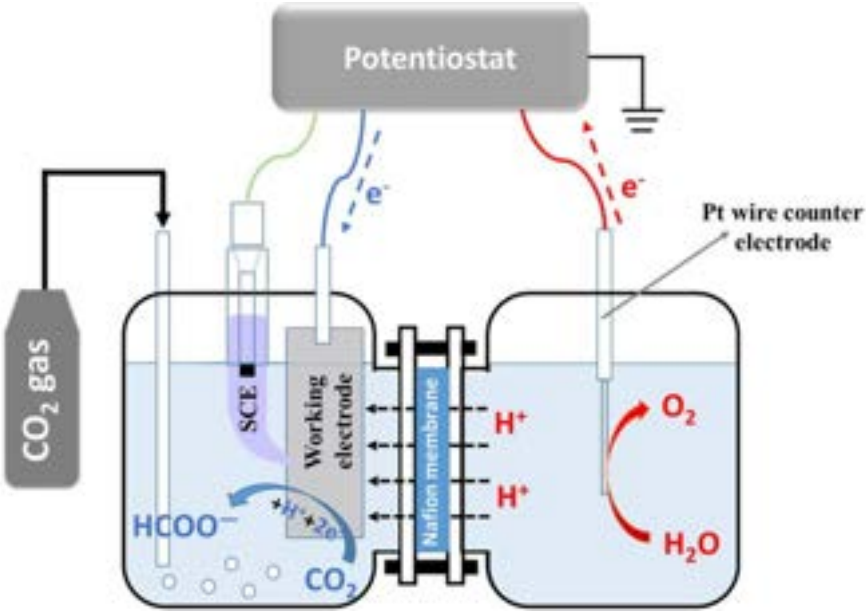
Product	Hydrogen demand	Reaction heat	Breakeven hydrogen price ($/kg)		Market
	H_2/CO_2	kJ/mol	No carbon tax	Carbon tax = USD100/t-CO_2	USD/tonne, approximately
Methanol	3	-49	**3.30**	**3.37**	526
DME	3	-61	0.11	0.26	63
Ethylene	3	-40	0.19	0.31	119
Methane	4	-160	-0.09	-0.04	13
Formic acid	1	+15	2.43	2.62	120

Methanol is a gateway chemical



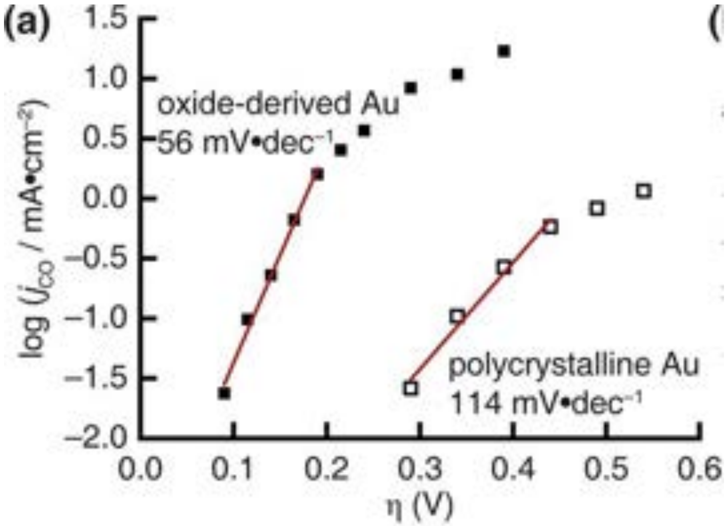
Electrochemical CO_2 reduction

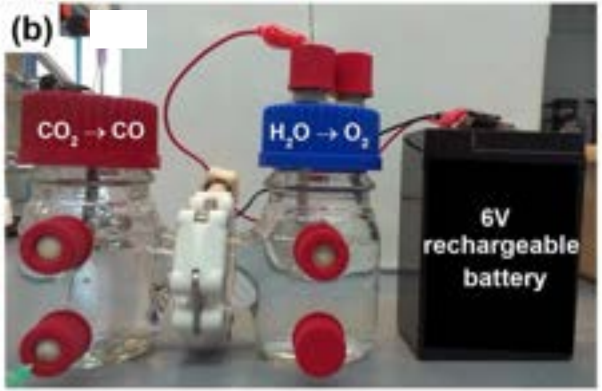
- Near-ambient-pressure operation
- Driven by renewable electricity
- Direct hydrogen supply from water electrolysis (electro CO_2 reduction)
- Oxygen as byproduct
- Intermittent operation
- Catalysts determine product distribution
- Requires electrolytes



Challenges in electrochemical CO_2 reduction

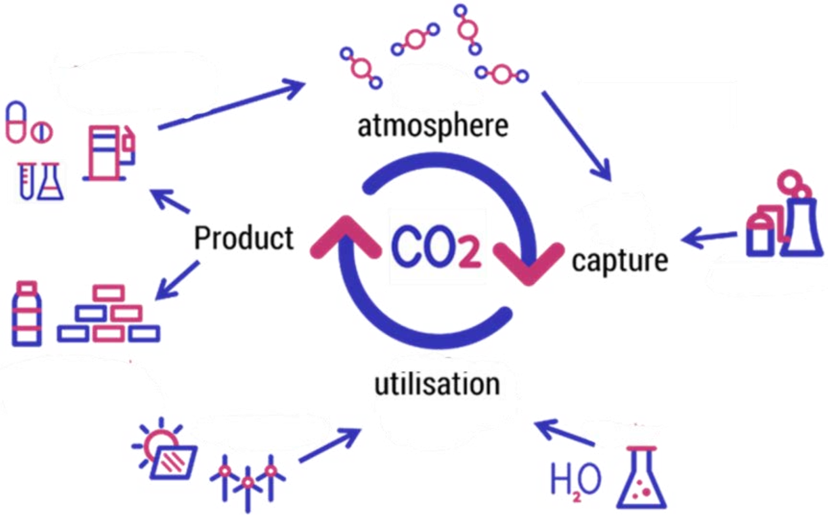
- Overpotential determines energy penalty
- Scaling up
- Demand for noble metals
- Product extraction and purification
- Three phase systems – reactor design challenges



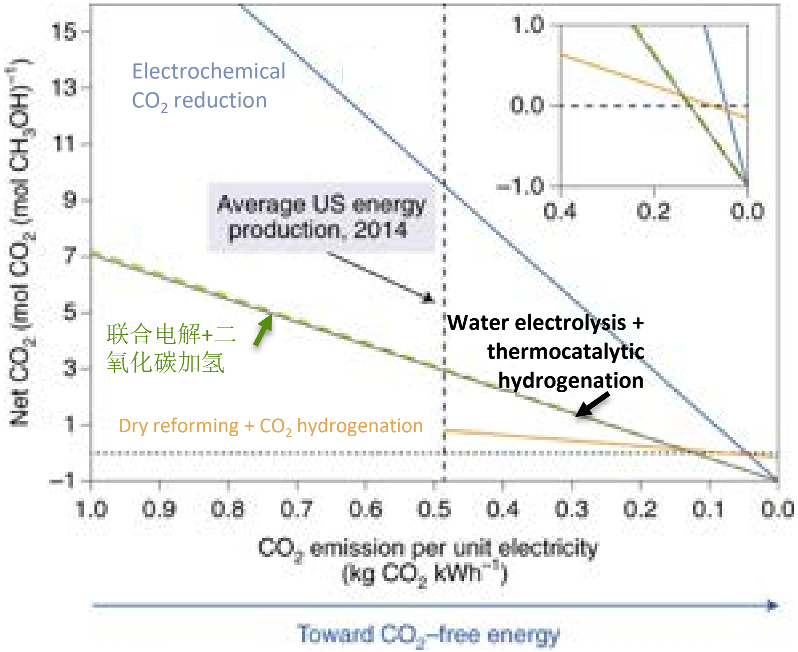


Yihong Chen; Christina W. Li; Matthew W. Kanan; *J. Am. Chem. Soc.* **2012,** 134, 19969-19972.

Hybridising electrochemistry and thermal chemistry to achieve CO_2 recycling



Source of Image: CO2Chem



Tackett et al. *Nature Catalysis* 2, (2019): 381.

Thank you

Q&A