CO_2 Capture and Storage (CCS)

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My Career and Qualifications

- Education
  - Ph.D. (Mechanical) University of Michigan-Ann Arbor
  - M.S.E. (Aerospace) University of Michigan-Ann Arbor
  - M.A.Sc. (Mechanical) University of Windsor, Canada
  - B.Eng. (Mechanical) NED University, Karachi, Pakistan
- Experience
  - Northern Illinois University (2019 – present)
  - University of Michigan-Flint (2017 – 2019)
  - Masdar Institute (2010 – 2017)
  - University of Michigan-Dearborn (1997 – 2010)
  - Visiting Affiliations: MIT, NUS, AUS, Oak Ridge, Ford

CCS Background

- A major source of the emissions of carbon dioxide (CO_2), a greenhouse gas that contributes to global warming, is the combustion of fossil fuels.
- Fossil fuels contribute more than 80% of the world primary energy, a percentage that is very likely to remain unchanged for decades to come.

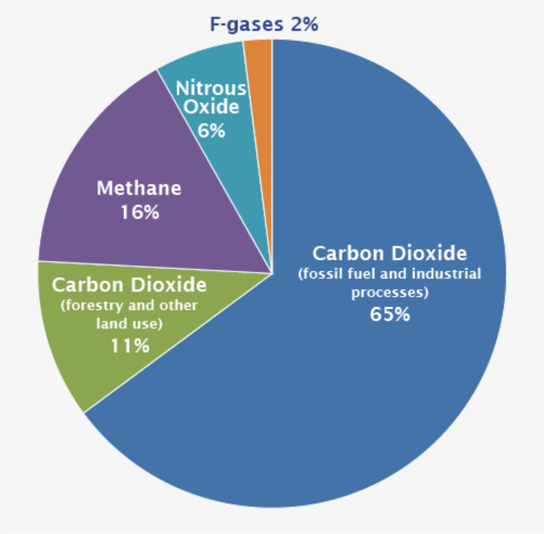
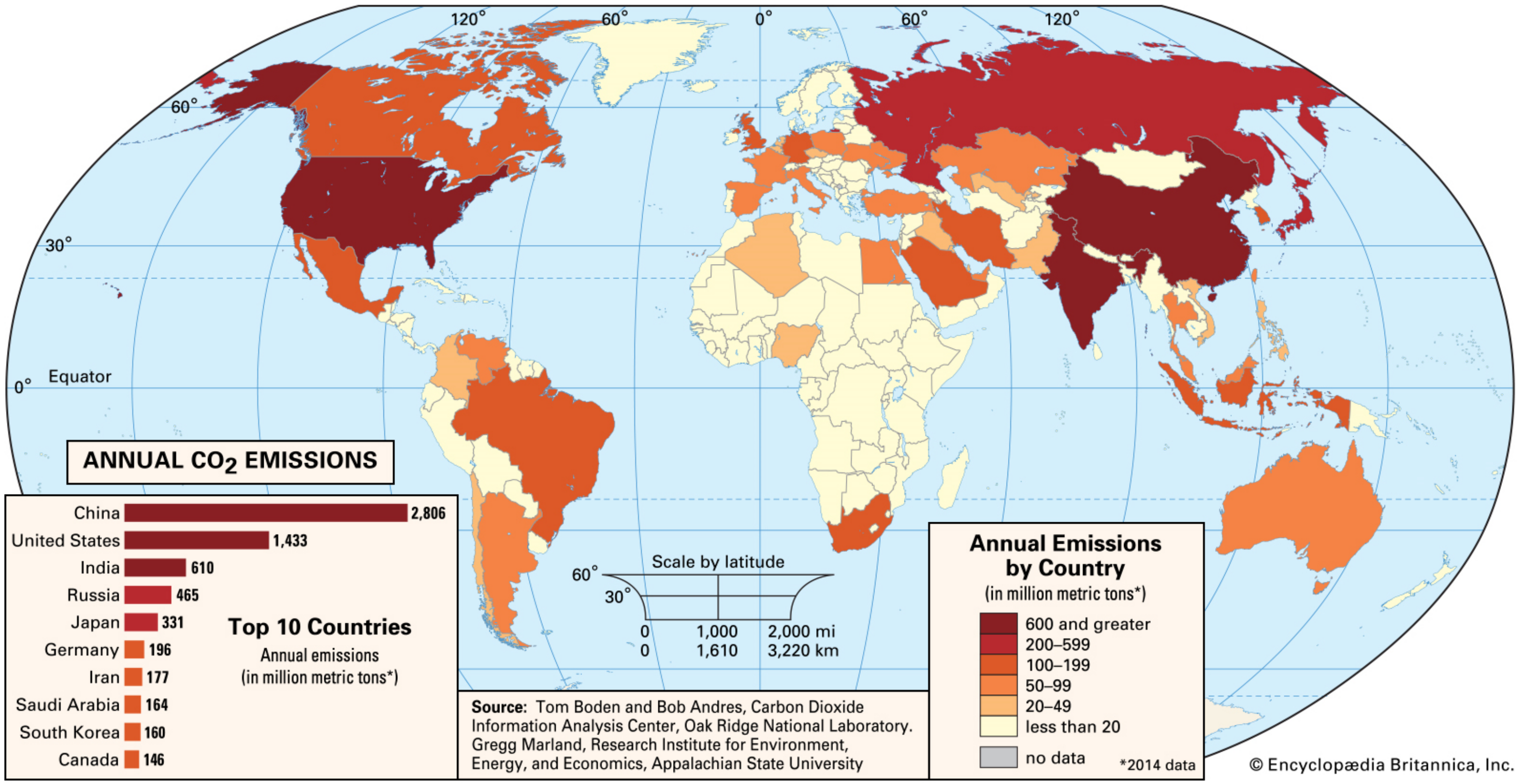


Figure: Global Anthropogenic Greenhouse Gas Emissions in 2010 (based on CO_2 equivalent)

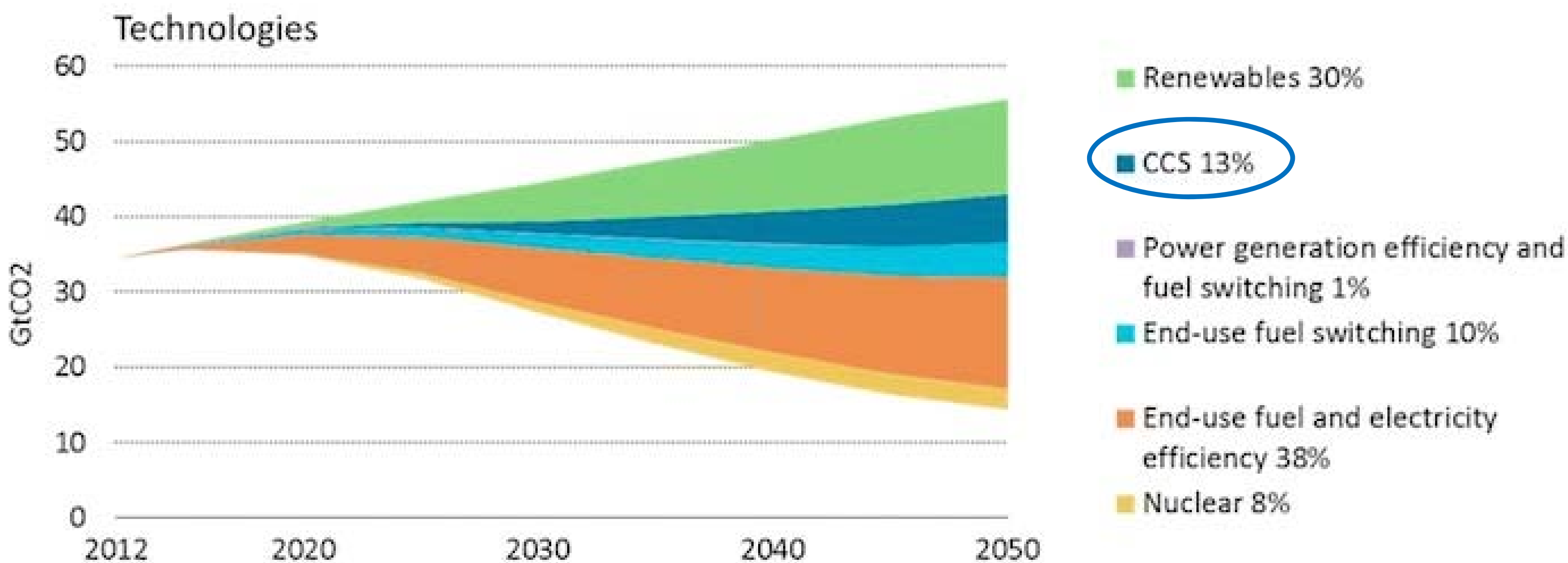
Reference: IPCC 5th Assessment Report: Mitigation of Climate Change 2014

Map of Annual CO_2 Emissions By Country



- There is growing interest in reducing/eliminating the use of fossil fuels by developing alterative/renewable energy sources.
- Zero carbon technologies shall not meet all the energy demand in near future.

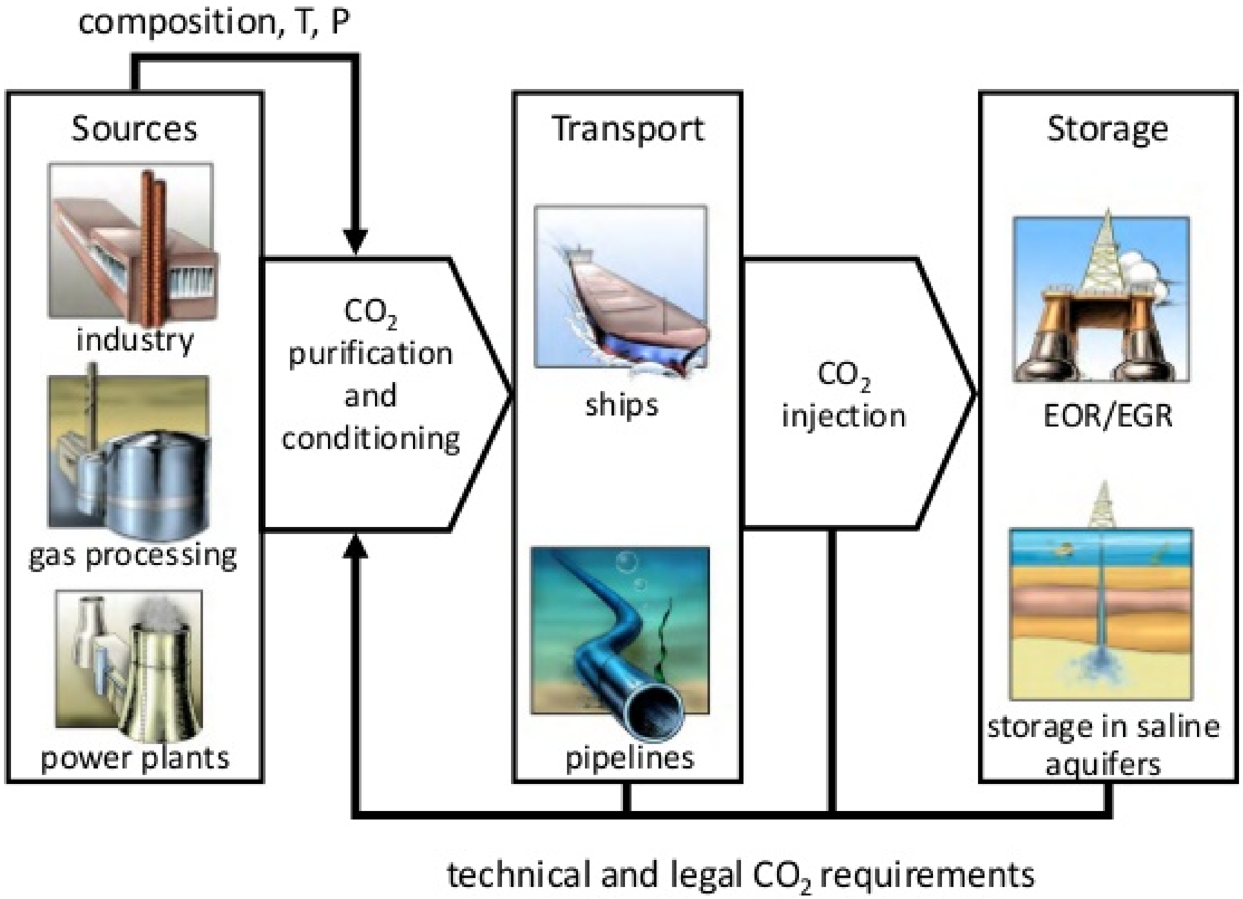
Key Technologies Forecasted for CO_2 Emission Reductions



Reference: *IEA, Energy Technology Perspectives, 2015*.

Carbon Capture and Storage is an important strategy in CO_2 reduction

CCS Value Chain



Reference: *Morin, A., SINTEF Energy Research, Workshop EC FP7 Projects. 2014*.

Typical Cost Elements of CCS

illustrative break-out of cost (capex plus opex) per tonne of CO_2 avoided

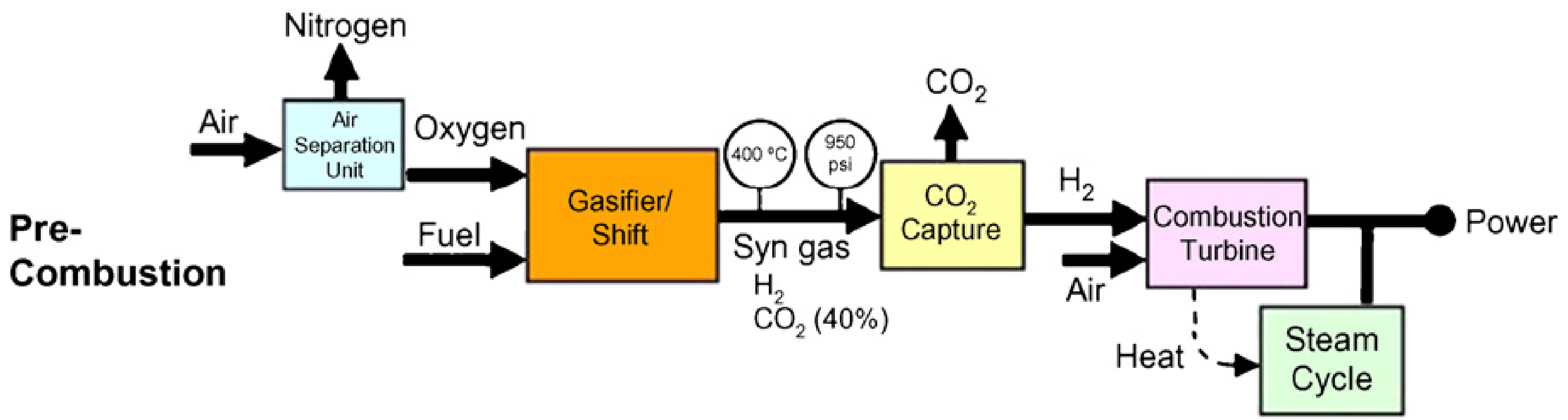
Capture	Compression	Pipeline Transport	Underground Injection
70%	5%	10%	15%
		scales with distance and offshore	negative for EOR

Sources: CCP Phase 1, MIT.

Reference: *Ward, G., Wikes, M., Growth and Future of CCS in Europe, GEO ExPro, 15, 2018*.

Approaches for CO_2 Capture

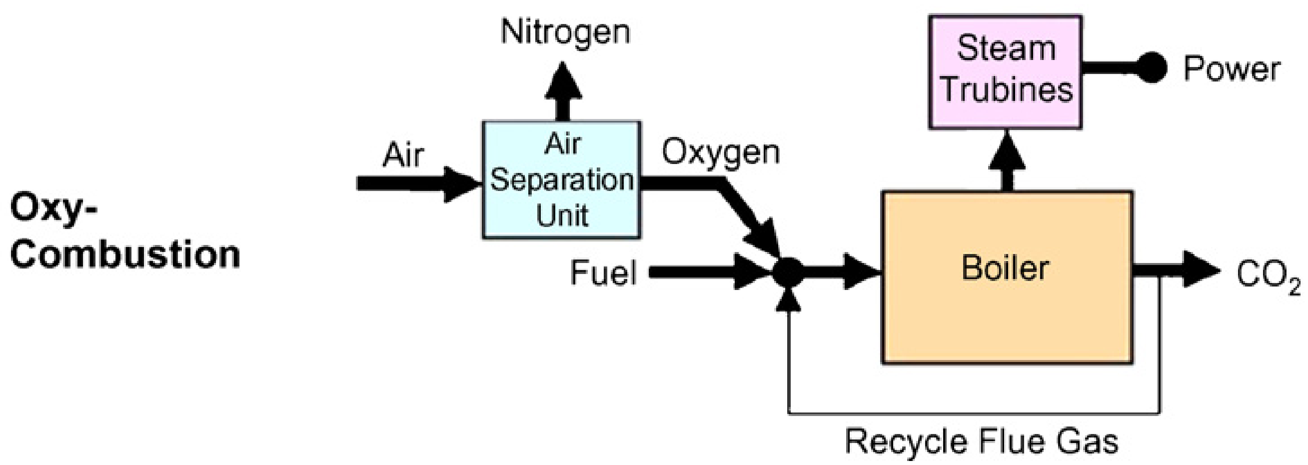
- Three commonly proposed approaches for CO_2 capture:
  - Pre-combustion capture: CO_2 is removed from the fuel prior to combustion through gasification or reforming followed by water-gas shift.



Reference: Figueroa, J.D., Fout, T.E., Plasynski, S.I., McIlvried, H.G., & Srivastava, R.D. (2008). Advances in CO_2 capture technology—The U.S. Department of Energy's Carbon Sequestration Program

Approaches for CO_2 Capture (cont'd)

- Oxy-fuel combustion: Pure oxygen (obtained through the cryogenic nitrogen separation from air) is used instead of air in the combustion process.



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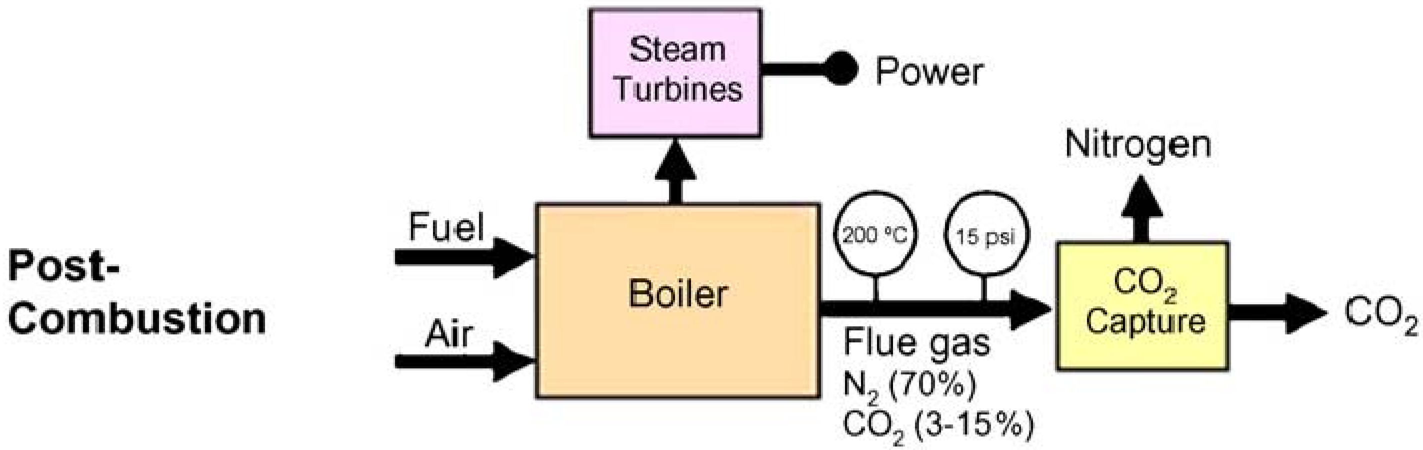
Approaches for CO_2 Capture (cont'd)

- Post-combustion capture: CO_2 is separated from the flue gases using chemical solvent.



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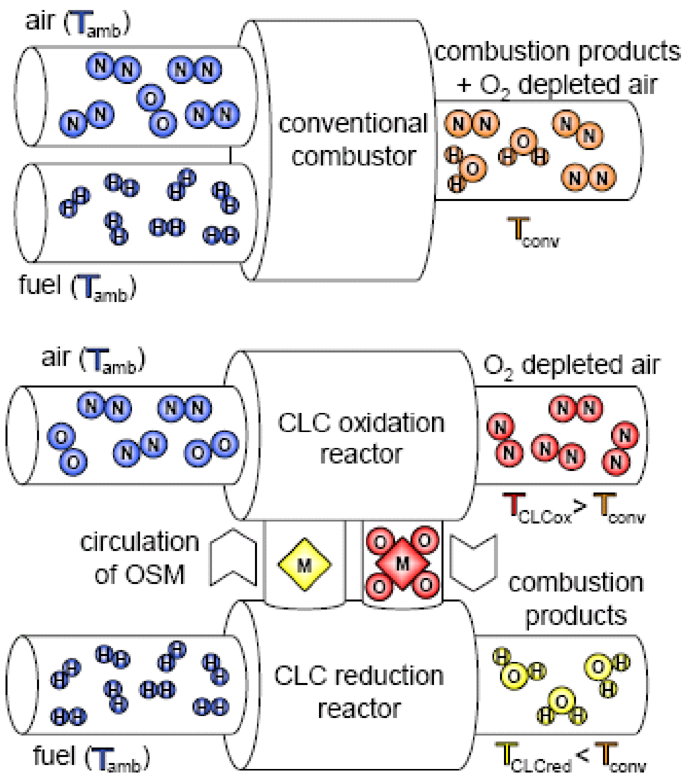
Innovative CO_2 Capture Technology

- Chemical looping combustion (CLC) offers a potentially attractive alternative to capture CO_2 with a significantly lower energy penalty than other technologies.
- Advantages:
  - Inherent CO_2 capture
  - Higher energy conversion efficiency
  - Lower NO_x Emissions

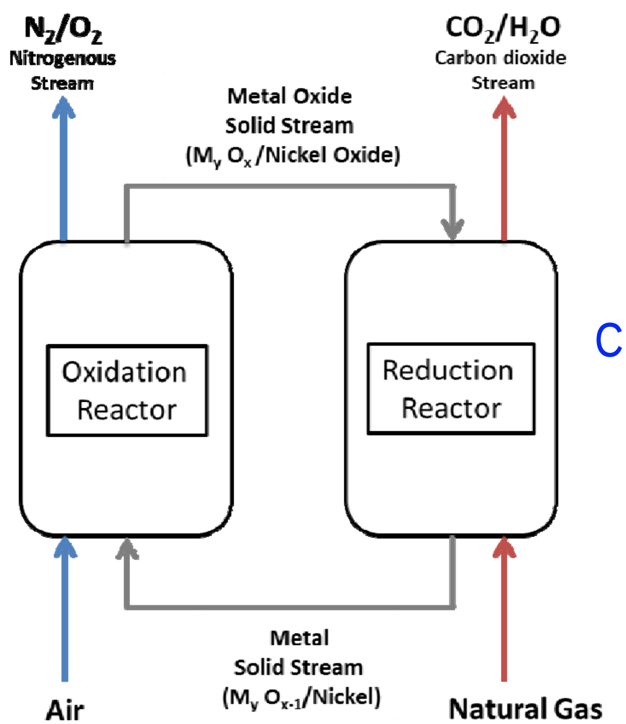


Schematic of Conventional and CLC Processes

CLC Process

- The main idea of CLC is to split the combustion of the fuel into two separate reactions carried out in two separate reactors: an oxidation reaction and a reduction reaction, by introducing suitable metal oxide as an oxygen-carrier that circulates between the two reactors.

$Me + 1/2O_2 \rightarrow MeO$
(Oxidation Reactor)



$CH_4 + 4\ MeO \rightarrow CO_2 + 2H_2O + 4Me$
(Reduction Reactor)

Research Issues: Development of a Suitable Oxygen Carrier Material

- Selection of a suitable oxygen carrier material is critical in the design of a CLC system.
- The material must possess desirable chemical kinetic characteristics under both oxidizing and reducing environments; be chemically stable under repeated oxidation and reduction cycles at high temperature; and be resistant to agglomeration.
- The cost and environmental impacts also affect the choice of oxygen-carrier material.

Research Issues: Oxygen Carrier Material (cont'd)

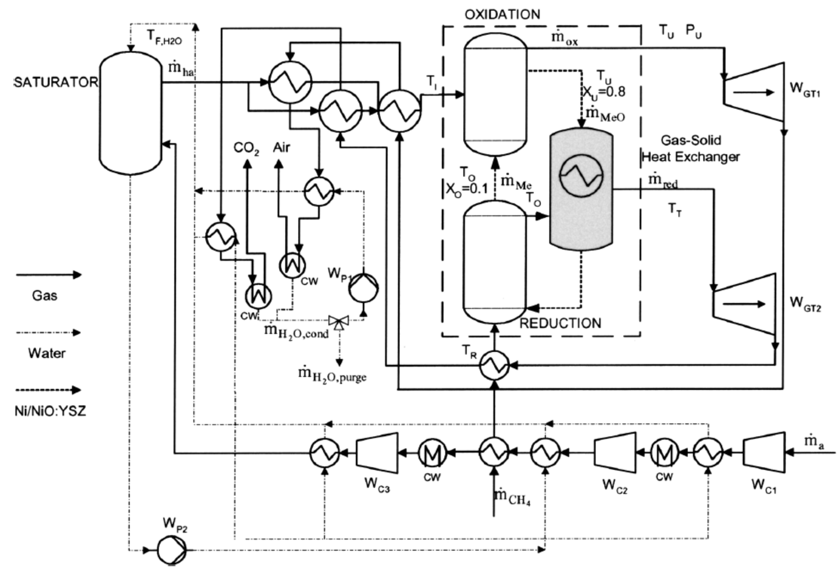
- Different transition metal oxides, such as oxides of Ni, Fe, Cu, Co, and Mn have been identified as possible candidates for the CLC process.
- The search of a suitable oxygen-carrier material for large scale application of CLC is still on.

Research Issues: Design of Oxidation/Reduction Reactors

- Desirable characteristics of an optimum reactor design:
  - Intimate contact between oxygen-carrier material and the gas phase species
  - Minimum energy penalty in separating gas and particles
  - Complete combustion of fuel
  - Maximum conversion of oxygen-carrier materials in the reactors
  - No CO_2 leakage from the fuel to the air reactor
- Fundamental understanding of the complex physicochemical processes occurring in reactors is lacking.

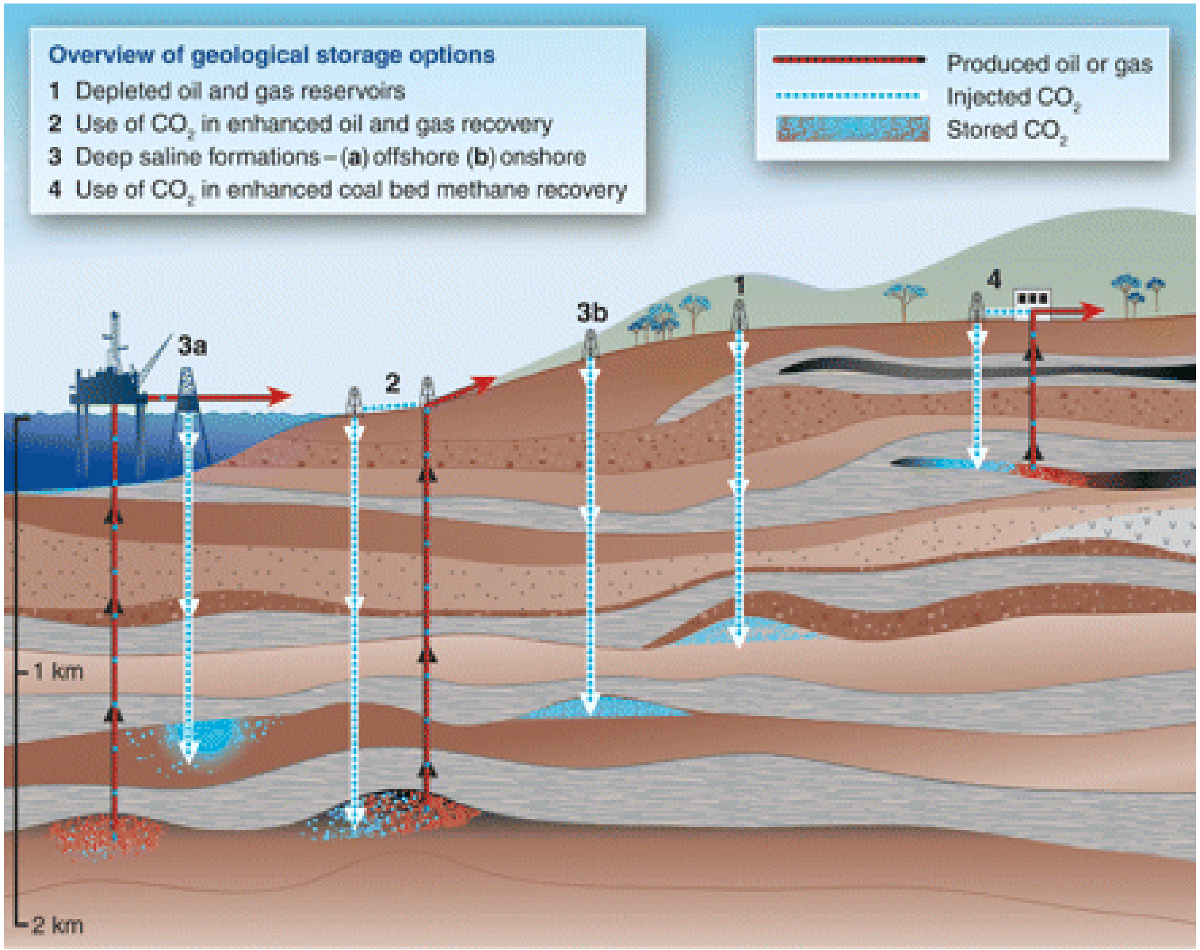
Research Issues: Integration of CLC Technology with various Power Cycles

- A better understanding of the integration of CLC technology with various power cycles is critical for the successful commercialization of integrated CLC power generation systems.
- System level modeling tools and large scale demonstration units are needed.



Brandvoll and Bolland, Journal of Eng. & Gas Turbines, Vol 125, 2003

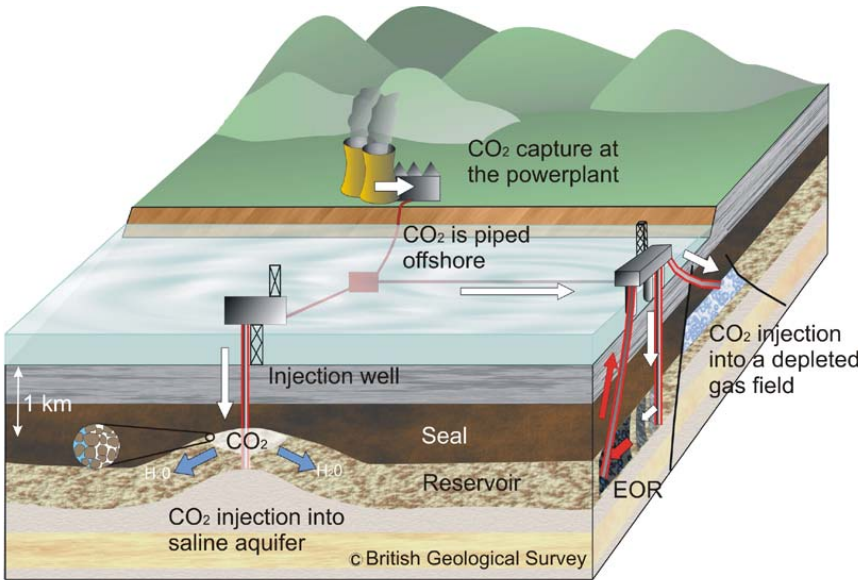
Overview of Geological Storage Options



Reference: *Orr, F.M., Science 325 (5948), pp. 1656-1658, 2009*.

Geological Storage of CO_2

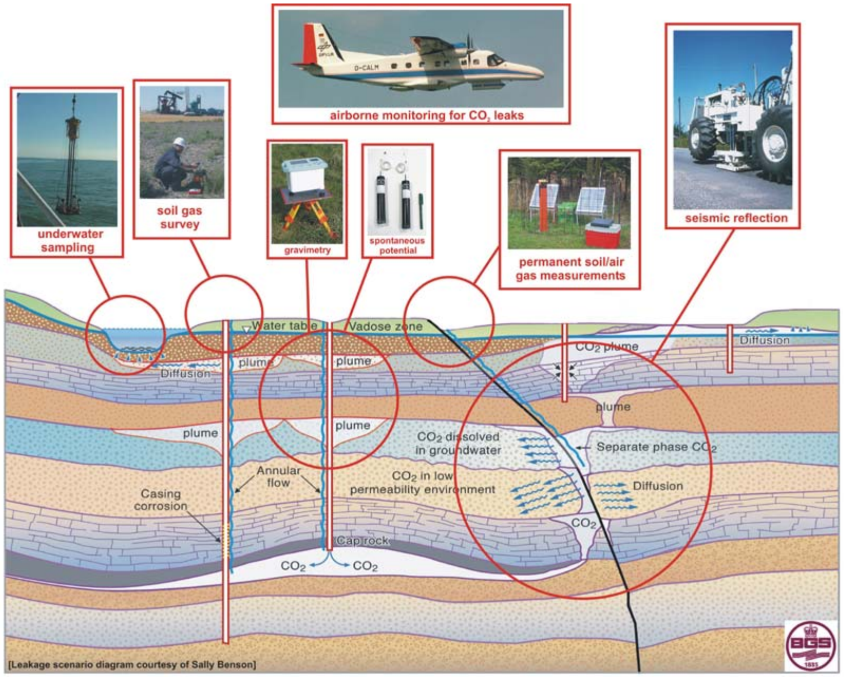
- CO_2 is injected into the pore-spaces of a reservoir rock.
- It permeates the rock, and displaces some of the fluid that was originally in the pore spaces.
- The injected CO_2 is buoyant and migrates towards the top of the reservoir until it reaches a caprock that prevents its further vertical migration.
- The amount of CO_2 injected into a rock may be limited by the permeability barriers such as faults



Reference: *https://iea.bgs.ac.uk/*

Monitoring of CO_2 Storage Site

- There are many tools available for monitoring of stored CO_2 sites
- Monitoring of stored CO_2 serves two purposes:
  - To provide confidence in predictions of the long-term fate of CO_2 in the subsurface and
  - To identify and measure any potentially hazardous leaks at the surface



Reference: *https://iea.bgs.ac.uk/*

CO_2 Storage Challenges

- Subsurface storage capacity
- Risk of long-term safety such as induced seismicity and the potential for forming fractures
- Risk of CO_2 release and long term liability
- Long term cost of monitoring stored CO_2
- Public acceptance

Example of a Research Project – Modeling Based CLC Reactor Design

Fluidized bed reactors are modeled from the view point of fluid dynamics, reaction scheme and kinetics, and heat balance involved in CLC process.

Fluid Mechanics

interactions between the reacting gases and solids

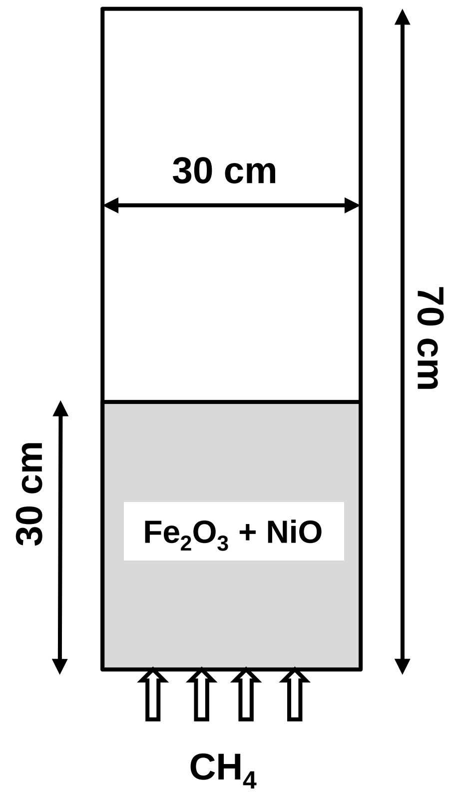
Reaction Kinetics

reactions occurring in the reactors and the kinetics involved

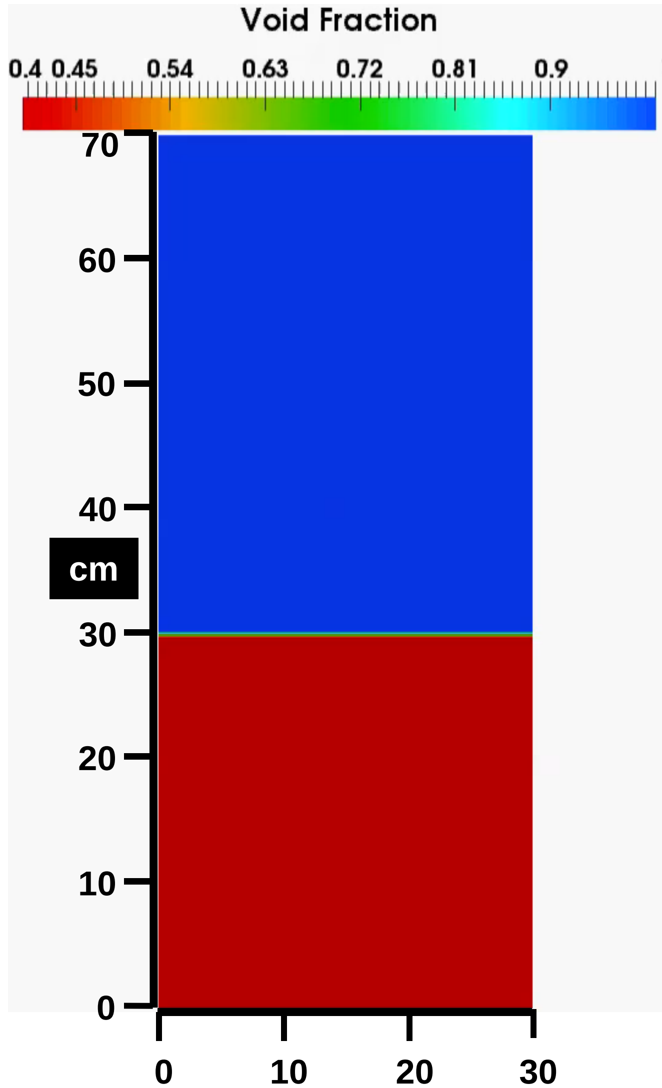
Heat Balance

temperature distribution and heat flux in the reactors

Use of CFD Modeling in CLC Reactor Design

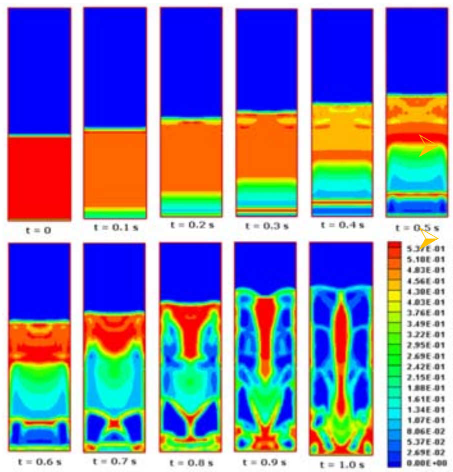


Particles: 40% bentonite, 45% NiO, 15% Fe_2O_3. Size: 128 μm diameter



CFD Modeling – Fuel Reactor Hydrodynamics

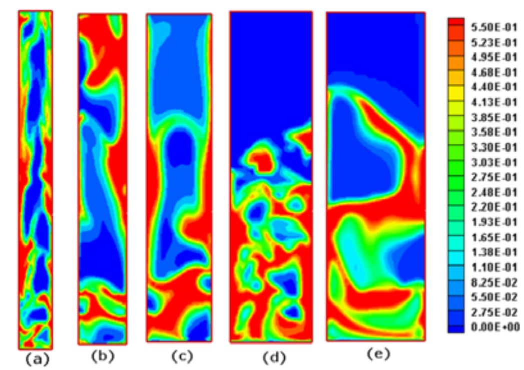
Bubble Hydrodynamics:



Rise, growth and development of bubbles

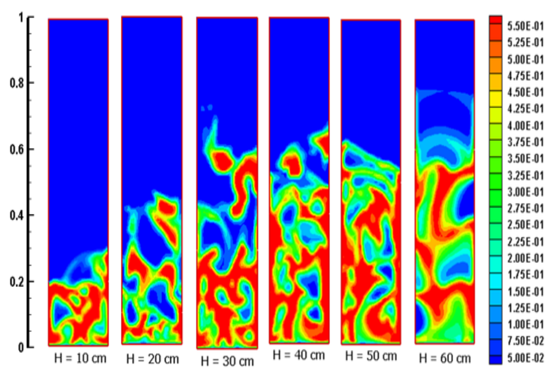
Column like structure at the center of the reactor

Effect of Bed Widths:



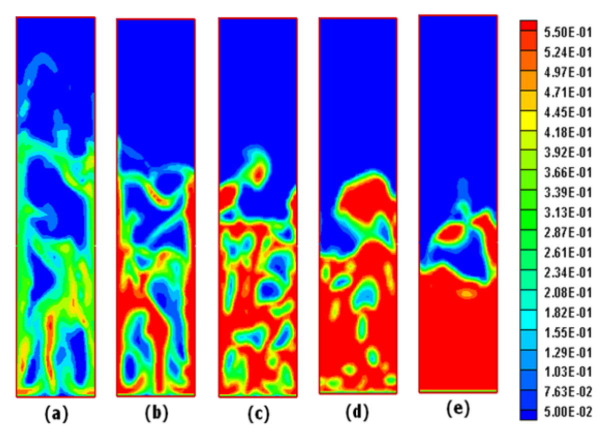
- Global mixing of gas-solid particles is more prominent for the reactors with smaller widths

Effect of Dense Bed Heights:



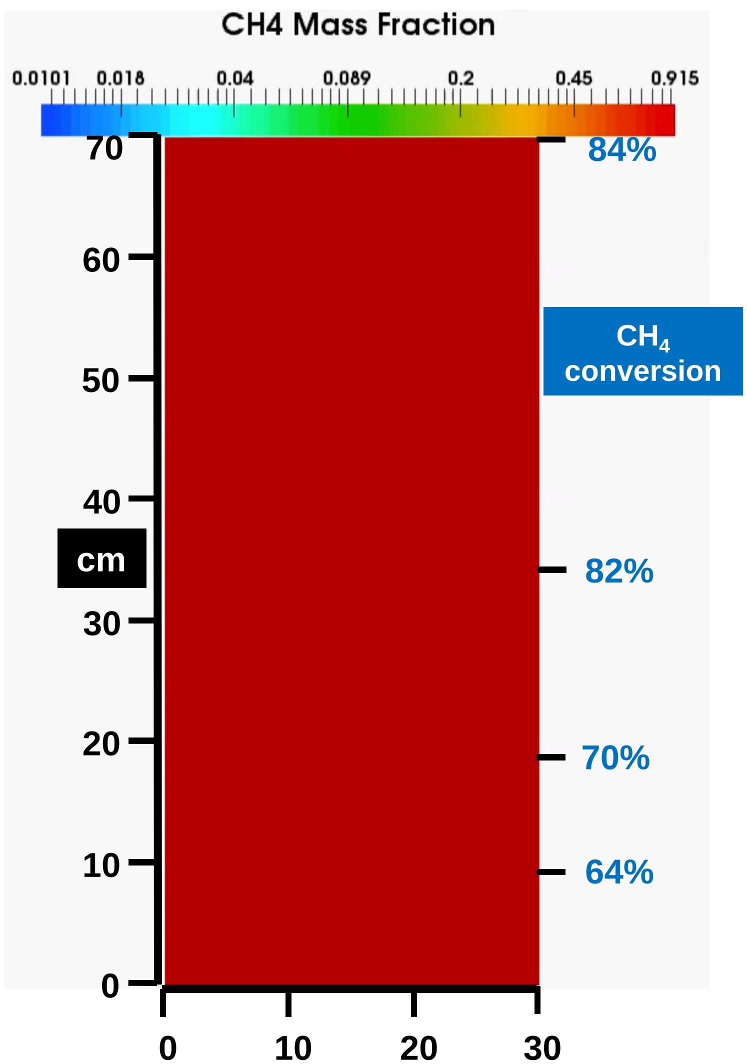
- With increase of static bed heights, the growth of bubble size decreases considerably thereby increasing the reaction rate in the reactor

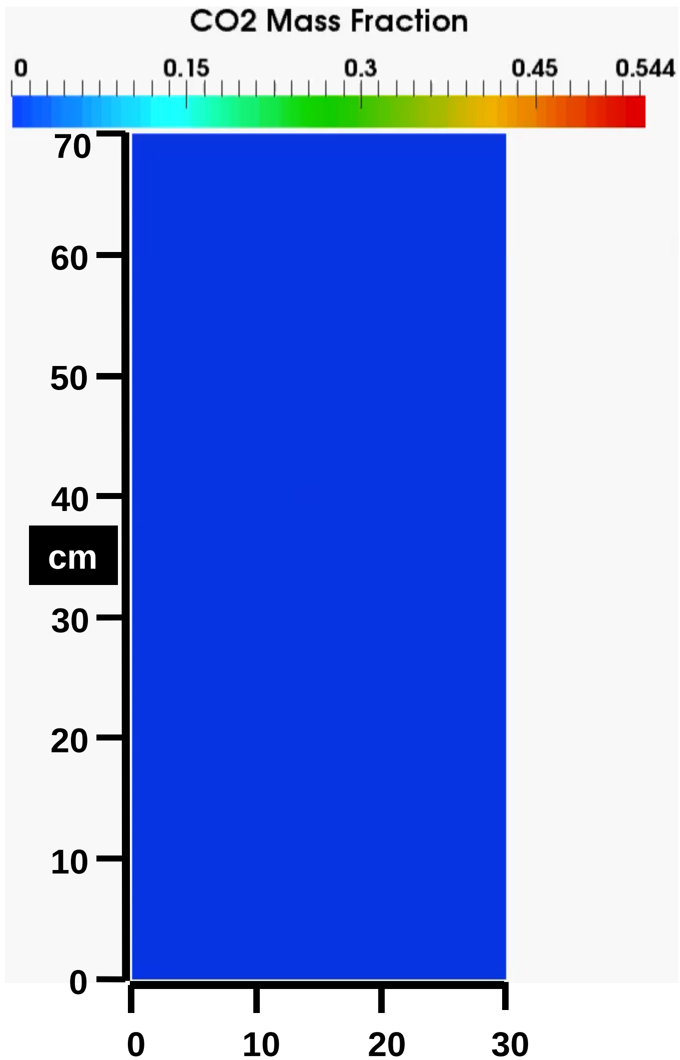
Effect of Particle Size:



- The conversion rate increases with the decrease of particle sizes.

CFD Modeling – CH_4 Conversion





Concluding Remarks

- CCS is a part of the solution for greenhouse gas emissions reduction
- There are no major technological barriers for the implementation of CCS
- Current cost of CCS is high and needs to be lowered for its large deployment. This requires research in novel and energy efficient capture approaches
- Need for improving legal framework allowing transport and geological storage of CO_2
- There is no clear business case for investment in CCS
- CO_2 capture can become more commercially viable by finding new pathways for the utilization of captured CO_2 as a feedstock to produce a wide variety of chemicals and materials

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