Advances in the Chemistry of CO_2 Capture

Chemical Sciences Roundtable - National Academies of Sciences

Creating solutions for a net zero world

Dr. Raghubir Gupta, Co-Founder / President

March 9, 2021

Susteon

What We Do

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Susteon Mission

To develop and deploy technologies that ***significantly reduce*** greenhouse gas emissions by enabling disruptive innovations in **CO_2 capture and CO_2 utilization** and **H_2 production**

Susteon Approach

De-risk technologies through extensive prototype development and testing while securing a strong IP position

Susteon Process

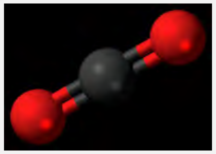
We Connect

- Academic / National Labs
- Dept. of Energy (and other Govt. agencies)
- Industry
- Private Sector / VC

We Create

Carbon Dioxide

- CO_2 Capture
- CO_2 Utilization



Hydrogen

- Blue / Green Production
- Modular Conversion
- Methane Pyrolysis

We Commercialize

- Discovery & Commercial Value Decision
- Leverage Industry and Lab Partners to Fail Fast
- Understand and Develop Go-To-Market Plan

Climate Change Affects Everything

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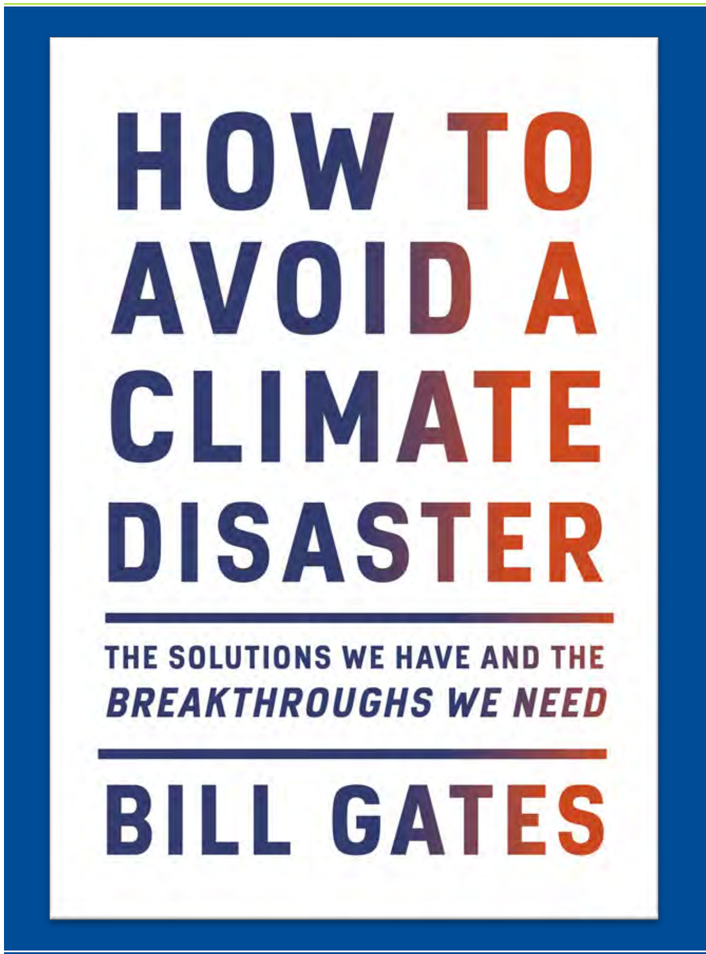

As Bill Gates outlines in his recent book, to solve Climate Change, we must reimagine the way we live as a society, specifically:

- ❑ How we plug-in
- ❑ How we make things
- ❑ How we grow things
- ❑ How we get around
- ❑ How we keep cool and stay warm

CO_2 plays a large role in solving these issues…

CO_2 Capture, Utilization, and Storage (CCUS)

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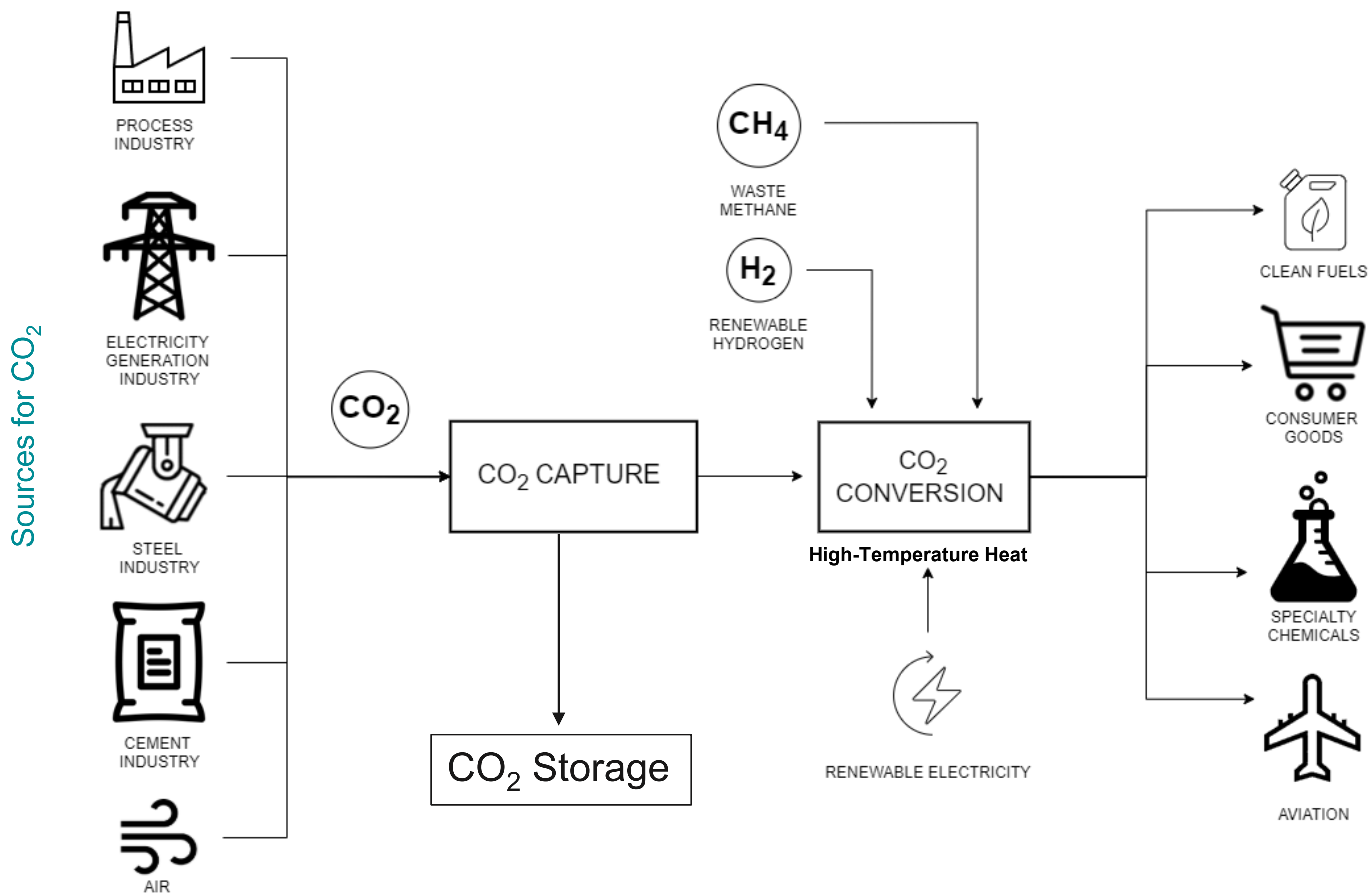
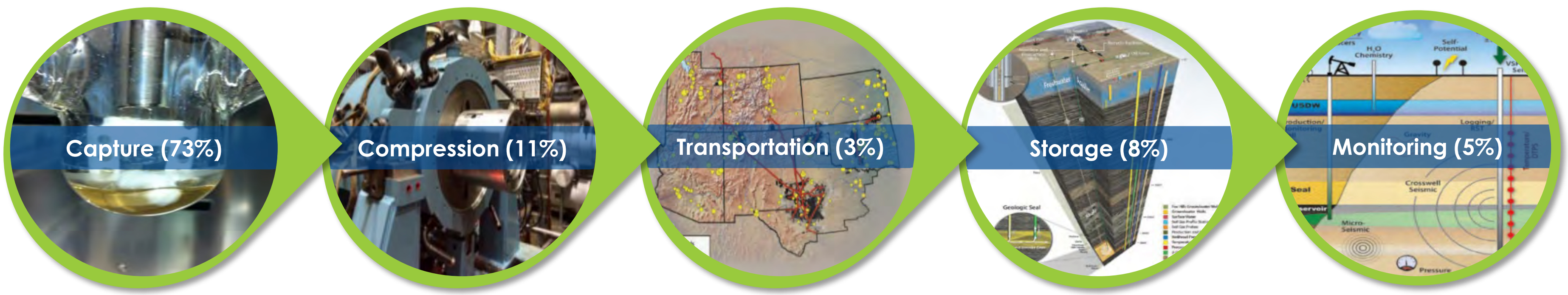
- Our current task is to tackle the **~40 GT/yr CO_2 emissions** that we are currently putting in the atmosphere.
- To do this, we need to **look at all sources of CO_2** and consider all methods of capture, utilization, and storage.
- The ongoing challenge is **lack of a regulatory framework, economic incentives, and poor understanding of CCUS value chain.**



CCUS Value Chain Costs



Source: NETL, Cost and Performance Baseline for Fossil Energy Plants, Revision 3, July 2015

CO_2 Capture Technologies

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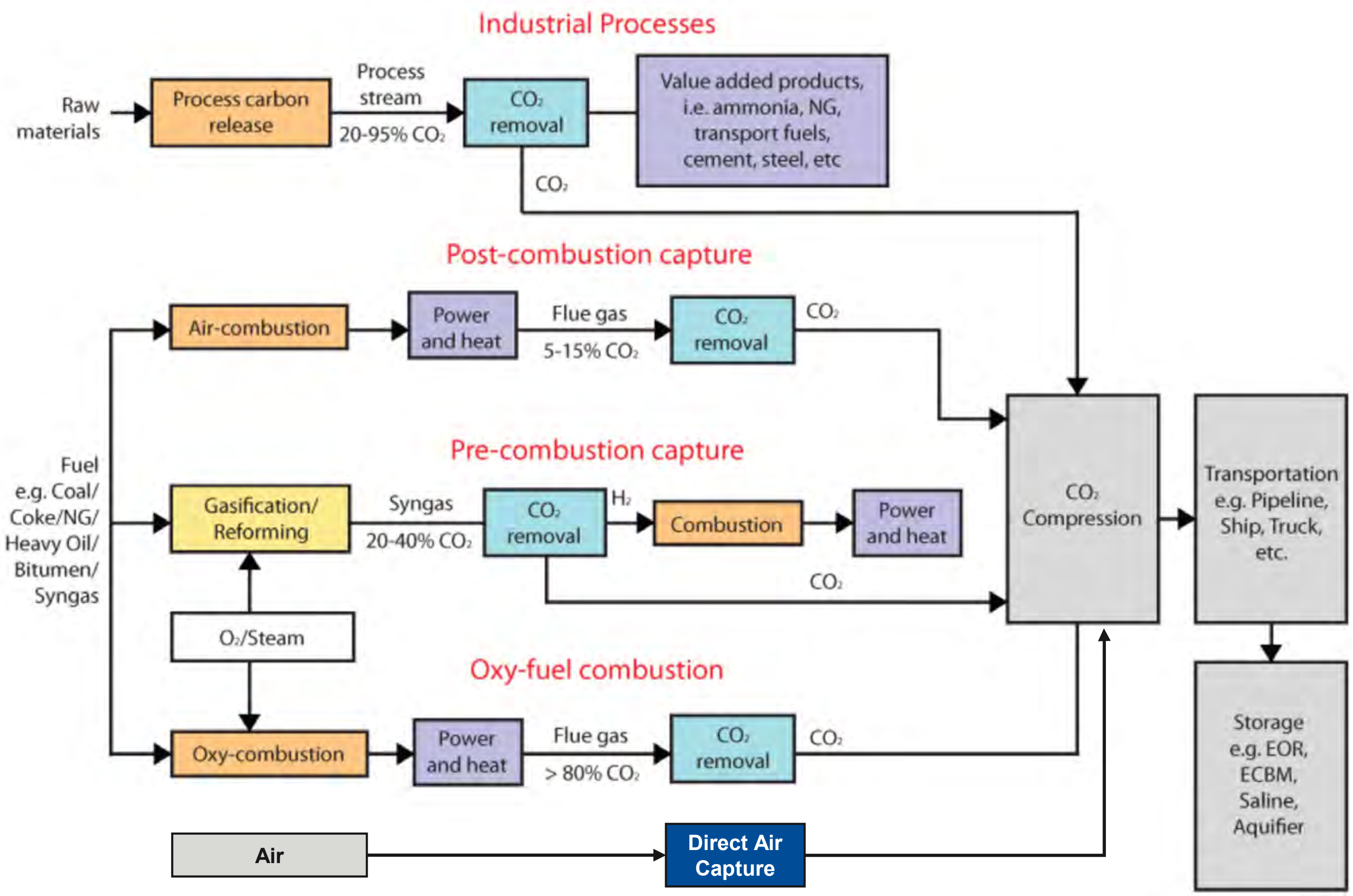
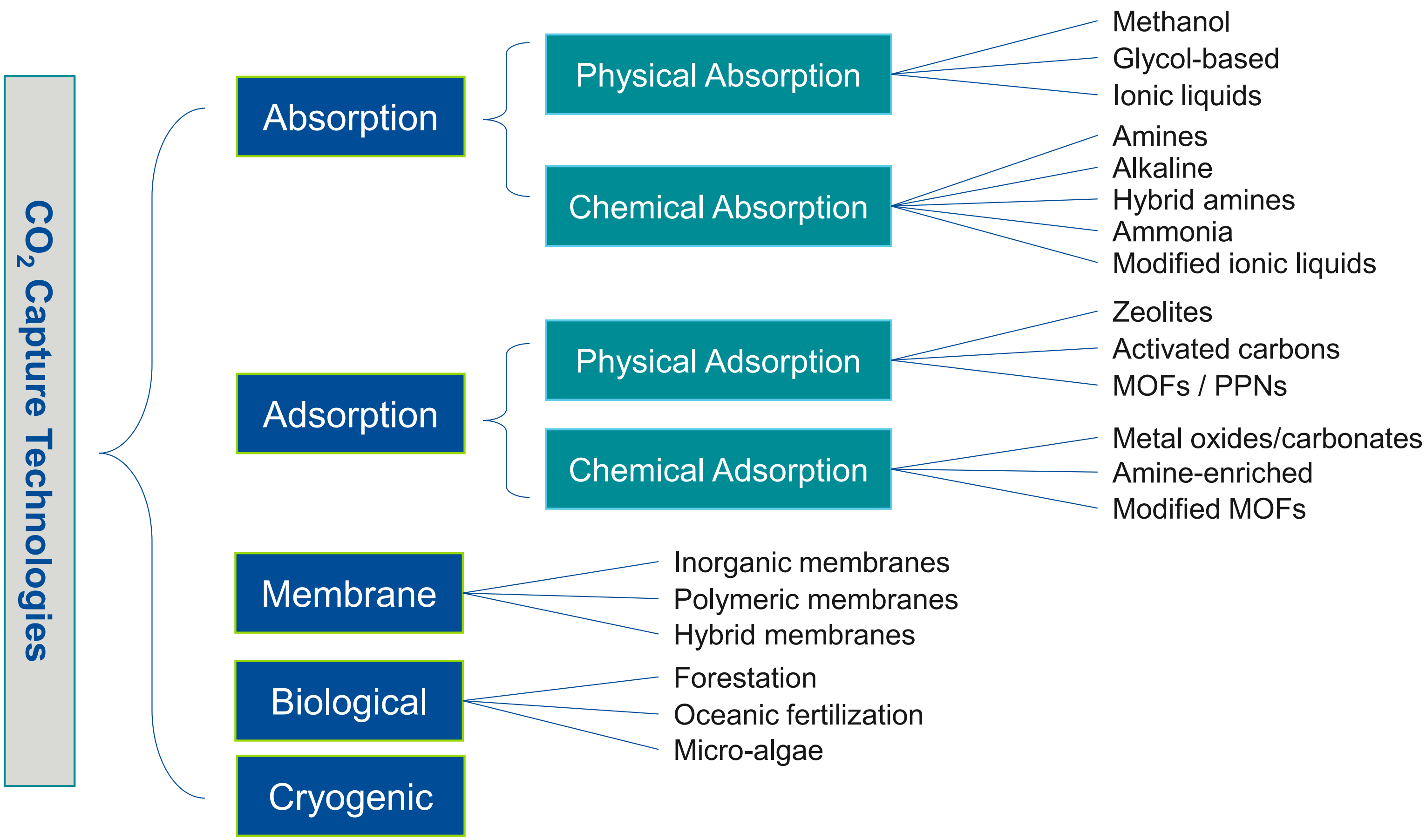


- These pathways represent **~50-60% of CO_2 emitted globally**.
- Essentially all fossil-based power requires **post-combustion capture**.
- Choice of CO_2 capture technology depends on the **CO_2 concentration, temperature, pressure, and other characteristics of gas stream**.

CO_2 Capture Pathways



Source: Song, 2020

Source Concentration – Challenge or Opportunity

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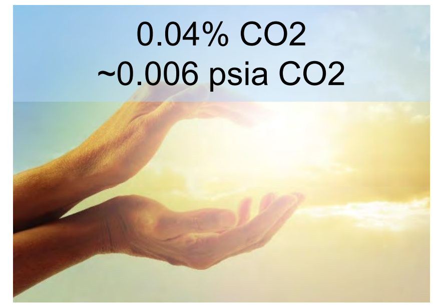
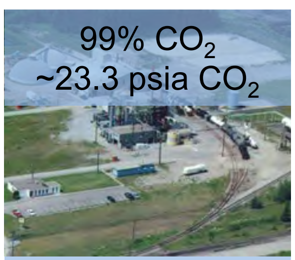
Coal Power Plant

Gas Power Plant

Air Capture

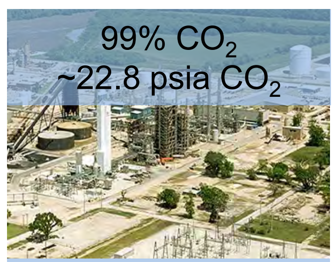


NG Processing Plant



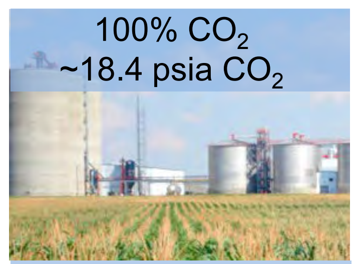
CO_2 vent

Ammonia Plant



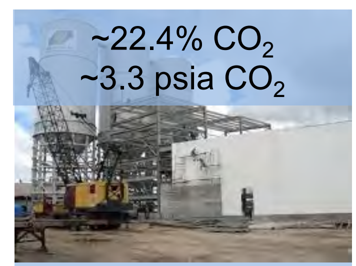
Stripping vent

Ethanol Plant



Distillation gas

Cement Plant



Kiln off-gas

Source: Cost of Capturing CO_2 from Industrial Sources, January 10, 2014, DOE/NETL-2013/1602

DOE/FE, 2021

Capture = Materials + Specific Process

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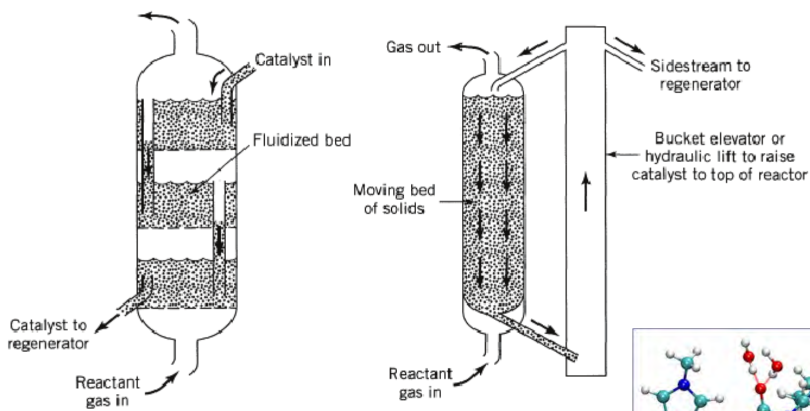
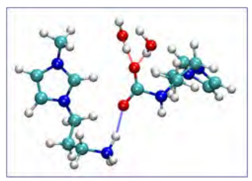
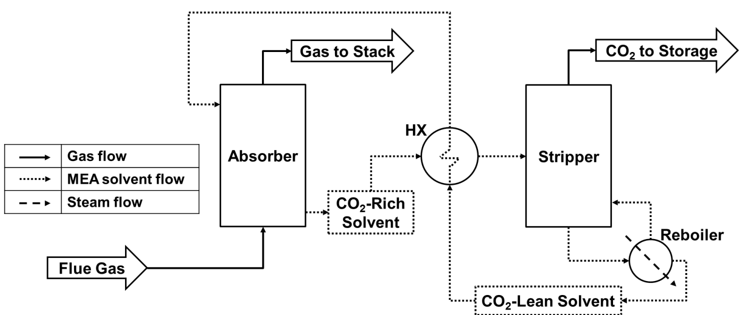
Reactor

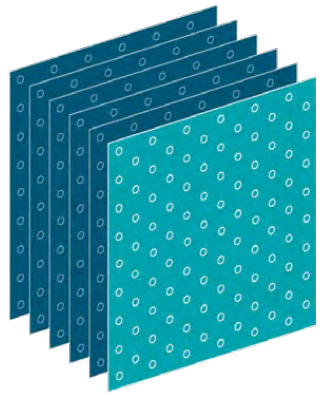


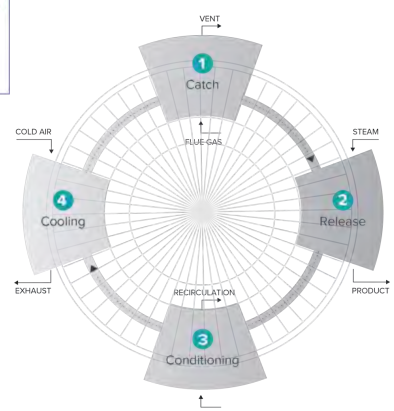


Solvents



Structured Laminates





Hollow fiber membrane

Sorbents

Membranes

Flat Sheet Membrane

Source: https://svanteinc.com/carbon-capture-technology/

Solvent-Based Post Combustion CO_2 Capture Technologies

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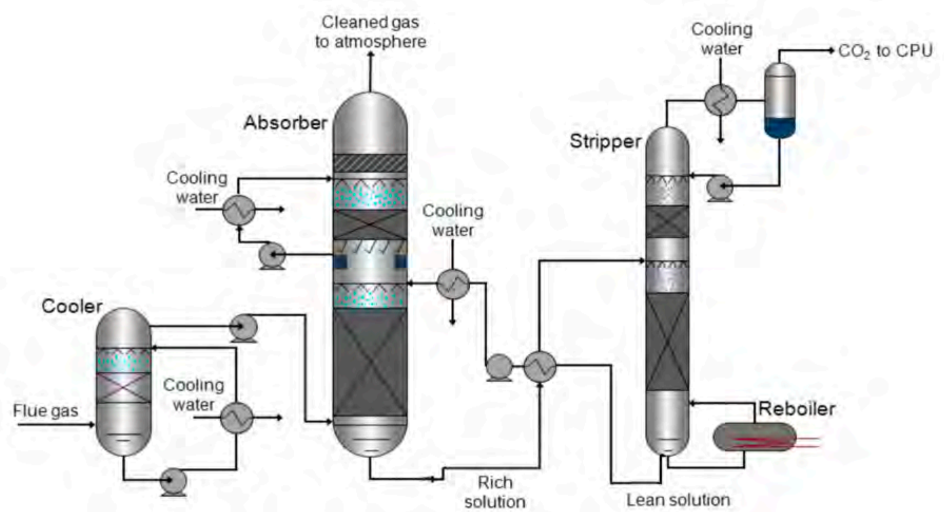
- CO_2 capture is a temperature swing absorption process.
- Typical solvents: Primary, secondary, tertiary, hindered amines such as MEA, DEA, MDEA, TEA, 2-AMP, …
- The CO_2 product has high purity >99% with traces of amine and oxygen.
- Process design parameters: CO_2 recovery, Gas flow rate, absorption/desorption rate, lean and rich amine CO_2 loading, approach to equilibrium and L/G ratio
- Advanced solvents that have lower regeneration energy requirement than existing amine systems, combined with high CO_2 absorption capacity and tolerance to flue gas impurities.
  - water-lean solvents,
  - phase-change solvents,
  - high performance functionalized solvents



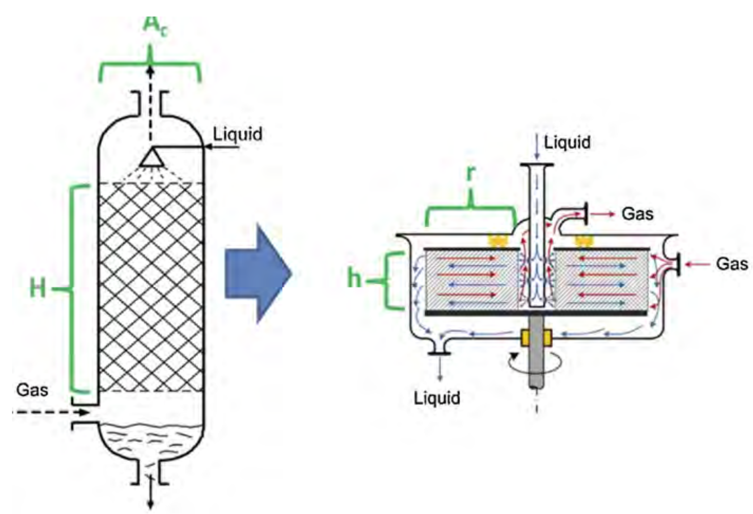
Commercialization Challenges
• Low overall absorption rate
• High regeneration energy
• Solvent loss due to degradation
• Solvent loss due to emissions
• Corrosion
• Wastewater treatment

Technology Providers
• **Mitsubishi** – KS-1 & KS-2 Solvents
• **Shell** – Cansolv
• **BASF** – OASE® blue
• **Aker Solutions –** ACC™
• **Fluor** - Econamine FG Plus℠

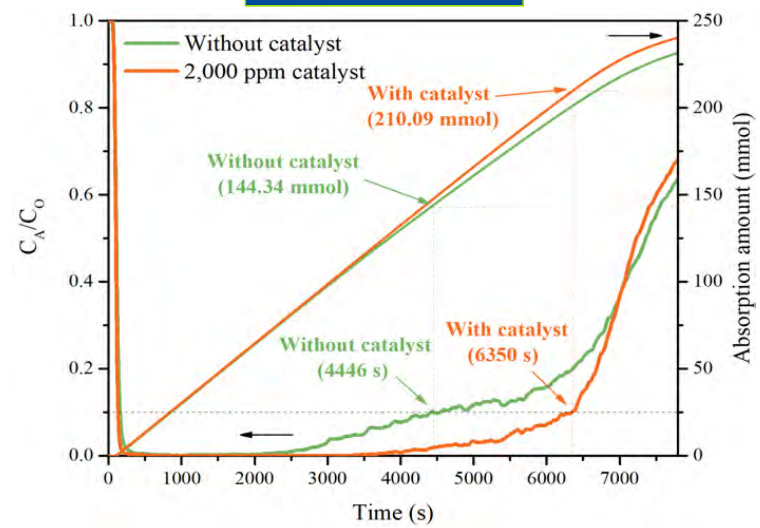
Source: Hasan, S.; Abbas, A.J.; Nasr, G.G. Improving the Carbon Capture Efficiency for Gas Power Plants through Amine-Based Absorbents. Sustainability 2021, 13, 72. https://dx.doi.org/10.3390/su13010072

Low Overall Absorption Rate for Amine-Based Solvents

- Low mass transfer rate between gas and liquid
  - Packing designs for better contacting
  - Absorber column height (high capex)
  - Process intensification based on increasing gas-liquid mass transfer rate
- Catalytic additives to enhance absorption rate



Susteon Technology



Adding 2,000 ppm of catalyst increased the absorption rate by 43%

Process intensification –Enhanced gas-liquid mass transfer using a rotating packed Bed (RPB)

Intensification factor ≈ 10 reported in literatures for acid gas treating

Source: Qian et al, I&EC 2012

High Regeneration Energy for Amine-Based Solvents

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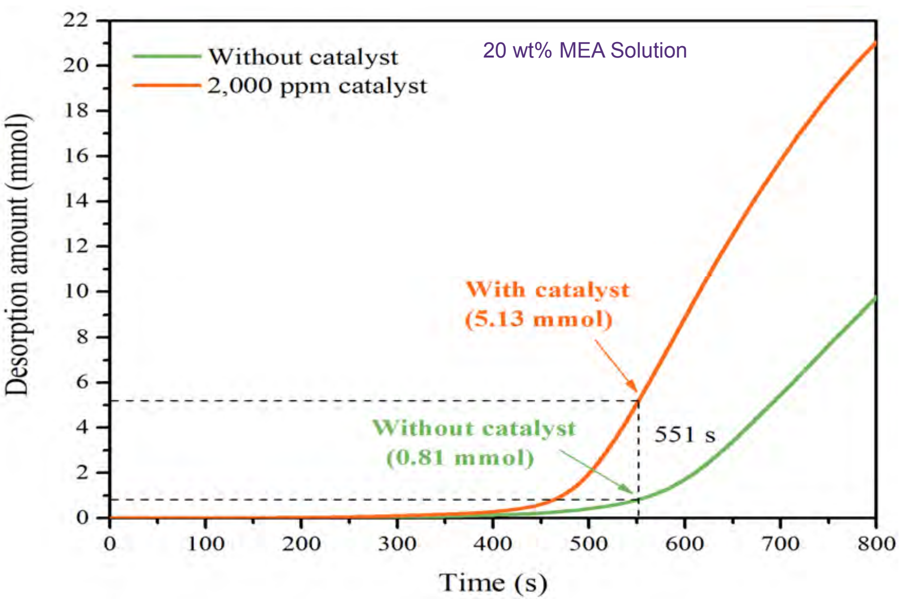
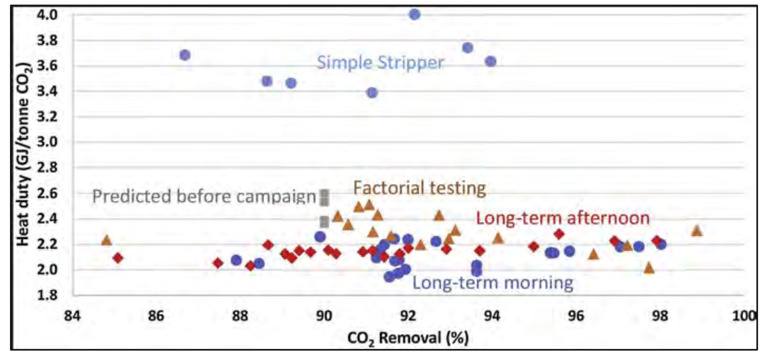
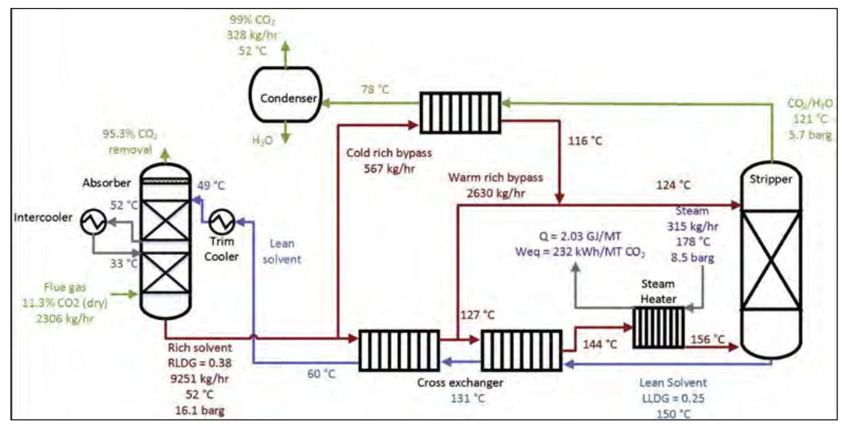
- Varies between 2.1 to 3.8 GJ/t of CO_2
- Largest contributor to CO_2 removal cost

Susteon's catalytic additive can potentially reduce overall energy by 30%





Process Optimization: Advanced Flash Stripper, ultrasound-assisted regeneration, etc.



Source: Gary T. Rochelle, Yuying Wu, Eric Chen, Korede Akinpelumi, Kent B. Fischer, Tianyu Gao, Ching-Ting Liu, Joseph L. Selinger, "Pilot plant demonstration of piperazine with the advanced flash stripper," International Journal of Greenhouse Gas Control, Volume 84, 2019,Pages 72-81,

Other Engineering Challenges

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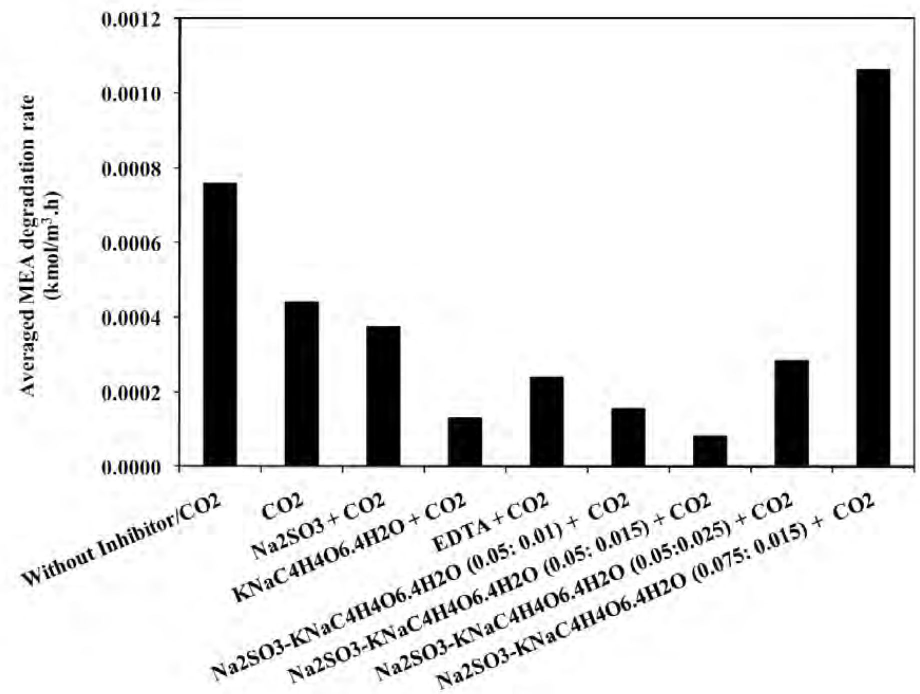
Oxidation, thermal degradation and side reactions with gas contaminants such as NO_x, SO_x and PM

Inhibitors:

- Oxygen scavengers, ex: Na_2SO_3
- Radical scavengers, ex: EDTA, NH_4OH
- Solvent loss due to emissions
  - Solvent entrainment (mitigated by de-mister)
  - Solvent volatility (mitigated by water wash)
  - Aerosol/acid mist induced emissions can cause significant amine loss (>10% total inventory per year)
  - No commercial solution yet to properly mitigate this issue
  - Emissions of solvent degradation products such as Nitrosamines and some lighter aldehydes imposes significant health and safety issues.



Source: Teeradet Supap, Raphael Idem, Paitoon Tontiwachwuthikul, Chintana Saiwan, “Investigation of degradation inhibitors on CO2 capture process,” Energy Procedia, Volume 4, 2011, Pages 583-590,

Sorbent-Based CO_2 Capture Technologies

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Physical Adsorption

- Alumina
- Zeolites
- Activated carbons
- MOFs
- PPNs

Chemical Adsorption

- Alkali oxides / carbonates
- Alkali earth oxides / carbonates
- Amine encapsulated

Commercialization Challenges

- CO_2 concentration in flue gas
- Competition with water
- Degradation with O_2
- Flue gas contaminants
- Long-term stability

Hybrid

- Amines + MOFs

Attrition

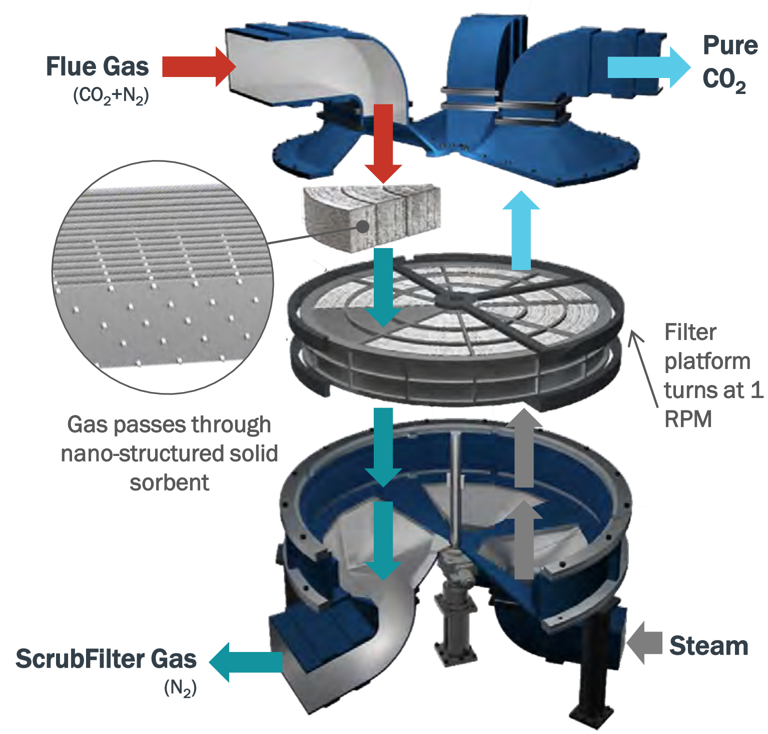
Corrosion

Disposal & Loss

Reactor/Process Design

- Fixed/Fluidized-bed reactor
- Structured bed (monolith/laminates)
- Gas/solid contacting
- Heat and mass transfer
- Pressure drop

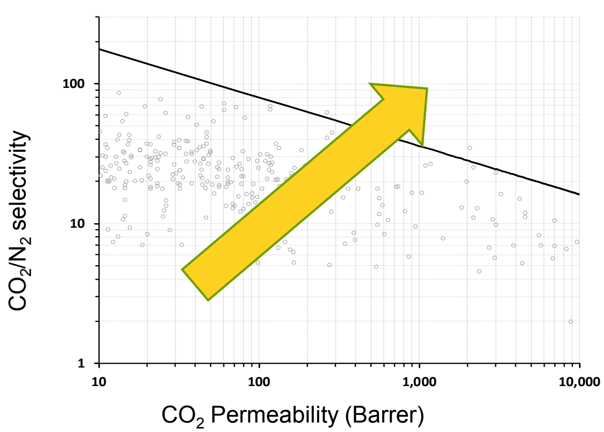
Svante CO_2 Capture System
(Exploded View)

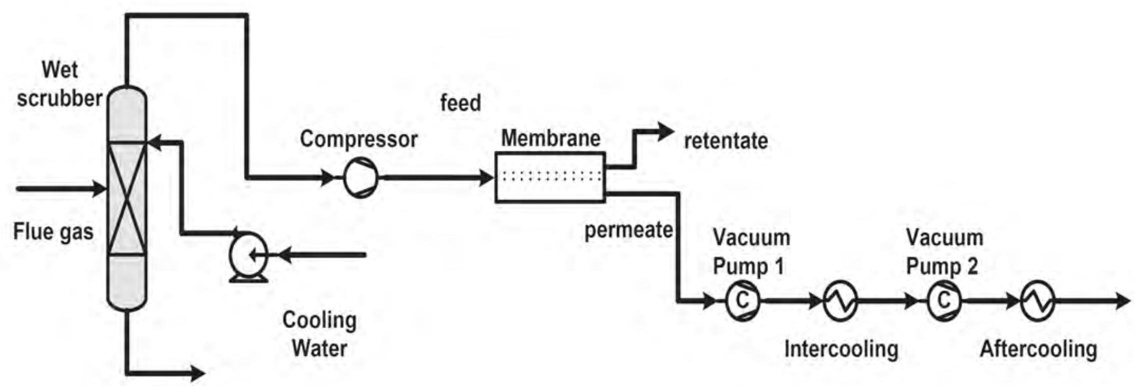


Membrane-Based Post Combustion CO_2 Capture Technologies

- Conventional polymeric membranes - polysulfone and cellulose acetate
- Non-facilitated transport membranes: “solution-diffusion” transport process whereby the permeate first dissolves into the membrane and then diffuses through it – Pebax, PDMS, MTR Polaris™ membranes
- Facilitated transport membranes: “solution-diffusion” characteristics + an active agent in the membrane to increase flux and selectivity
- Composite membranes (MOFs + polymers)

Selectivity and Flux





- **Good for CO_2 concentration of >10 vol%**
- **Typically, CO_2 purity is low and will require significant downstream purification.**
- **CO_2/N_2 selectivity >50 does not help, but higher flux leads to lower membrane cost**

Source: Yuan Wang, Li Zhao, Alexander Otto, Martin Robinius, Detlef Stolten, A Review of Post-combustion CO2 Capture Technologies from Coal-fired Power Plants, Energy Procedia, Volume 114, 2017, Pages 650-665,

Major CCUS demonstration projects

Air Products Facility (Port Arthur, TX) – operations began in 2013

- Built and operated by Air Products and Chemicals Inc. at Valero Oil Refinery
- State-of-the-art system to capture CO_2 from two large **steam methane reformers**
- **Over 5.0 million metric tons of CO_2** captured and transported via pipeline to oil fields in eastern Texas for **enhanced oil recovery (EOR)** since March 2013

ADM Ethanol Facility (Decatur, IL) – operations began in 2017

- Built and operated by Archer Daniels Midland (ADM) at its existing biofuel plant
- CO_2 from **ethanol biofuels production** captured and stored in **deep saline reservoir**
- **First-ever CCS project** to use new U.S. Environmental Protection Agency (EPA) Underground Injection **Class VI well permit,** specifically for CO_2 storage
- **1.3 million metric tons of CO_2 stored**, since April 2017

Petra Nova CCS (Thompsons, TX) – operations began in 2017

- Joint venture by NRG Energy, Inc. (USA) and JX Nippon Oil and Gas Exploration (Japan)
- Demonstrating Mitsubishi Heavy Industries' solvent technology to **capture 90% of CO_2 from 240-MW flue gas stream** (designed to capture/store 1.4 million metric tons of CO_2 per year)
- **Nearly 3.3 million metric tons of CO_2** used for **EOR** in West Ranch Oil Field in Jackson County, Texas since January 2017

Boundary Dam (SaskPower – operations began in 2016

- First (and the largest at the time) CO_2 capture plant from a **coal-fired power plant**
- Based on **Shell-Cansolv** license, engineered and constructed by SNC-Lavalin.
- Started in 2014, fully operational in 2016
- **3.7 million metric tones of CO_2 mostly used for enhanced oil recovery in Weyburn oil field, transportation via 66 km pipeline.**

DOE/FE, 2021

Direct Air Capture – Challenges and Opportunities

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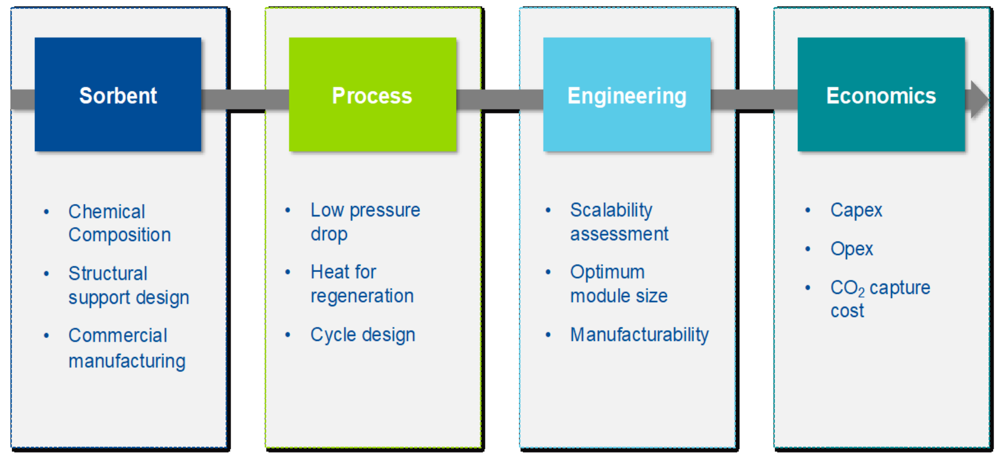
- **Highly selective**
  - N_2 + O_2 is 2500 times as abundant, H_2O: 10 – 100 times.
  - 1 ton of CO_2 removal requires flowing 3,200 tons of air (@50% removal)
- **Minimal binding energy**
  - $\Delta G_0 \leq -22\frac{kJ}{mol}$ (implies chemical binding) – Energy of mixing
- **Fast kinetics**
  - But tempered by inherently slow air-side transport
- **High capacity**
  - Particularly for thermal activation (lots of energy wasted in the bulk material)
- **Dirt cheap**
  - 1 ton CO_2 per kg of sorbent requires 10,000 to 100,000 cycles
- **Tough as nails**
  - Must survive >100,000 capture and regeneration cycles, sunshine, heat, cold, wind, dust …



Lackner, 2019

Direct Air Capture – Current Technology Status

- Several start-ups have working prototypes
- Different approaches, different markets
- Gaining experience, demonstrating costs
- Establishing a new technology
- New players are joining
- Research is proceeding at several universities:
  - ASU
  - Georgia Tech
  - Columbia University
  - ETH Zurich
  - Sheffield University
  - Zhejiang University

Commercial Interest is growing, carbon price incentives are starting, corporate world is investing

Lackner, 2019

CO_2 Utilization

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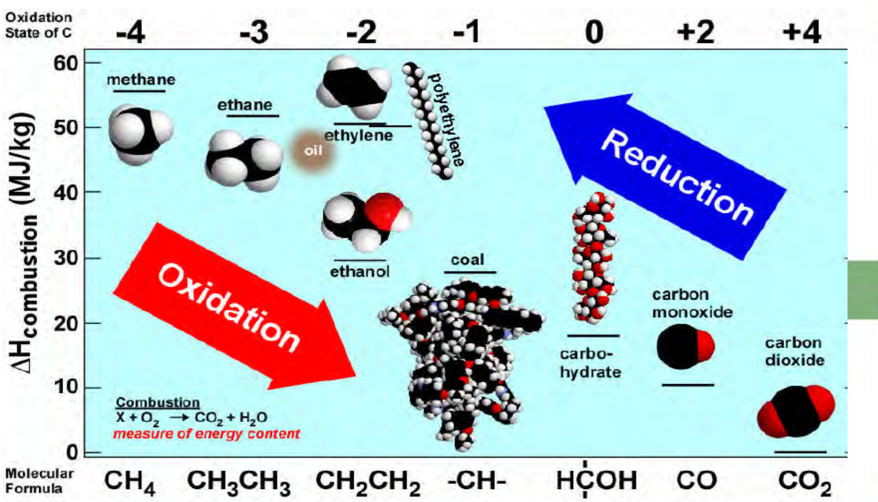
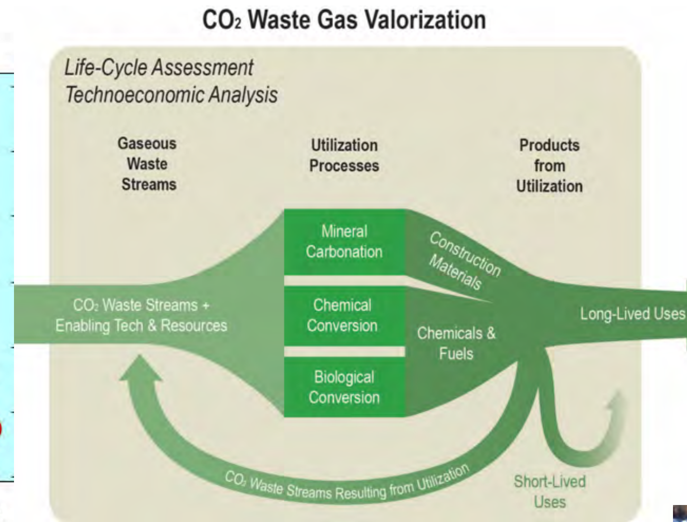
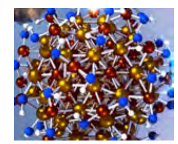




Thermochemical Challenges

Reliable, inexpensive carbon-lean energy



Catalysts

$CO_{2(g)}$
(-394 kJ/mole)

Thermodynamic Stability of CO_2

Gaseous Carbon Waste Streams Utilization: Status and Research Needs (2019)

DETAILS

256 pages | 7 x 10 | PAPERBACK

ISBN 978-0-309-48336-0 | DOI 10.17226/25232

If inexpensive reductants are available, CO_2 could serve as a carbon feedstock for traditional products.

Source: Banholzer, 2008

Summary

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- Current 51 GT/yr annual global GHG emissions, **CO_2 is responsible for ~80% of the GHG emissions**.
- **Chemical/energy industry** sectors account for **>50% CO_2 emissions**.
- **Solvent-based** CO_2 capture technologies are most advanced and can be used effectively for the point sources.
- There are still **scale-up and solvent degradation** challenges which are being addressed.
- **Regeneration energy** is the largest component of the CO_2 capture costs.
- **Direct air capture** has to be part of portfolio of solutions to achieve net zero emissions by 2050.
- CO_2 utilization offers some interesting options to make products, but **scale to match CO_2 emissions with utilization options is a challenge**.

We can take on this challenge

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Despite this daunting challenge, this problem is solvable; but only with an interdisciplinary approach and the best minds engaged, we can achieve this goal!

Thank you

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