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CO2 Capture and Utilization Emerging Markets and the Role of R&D

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CARBON CAPTURE AND UTILIZATION

A Section of SwRI

Benefiting government, industry and the public through innovative science and technology

Overview

- SwRI CED / CCU-PD Overview
- Market Trends for CC Tech
- Market Trends for CU Tech
- New Tech examples
  - SwRI
  - External
- Role of R&D
- Closing comments

CARBON CAPTURE AND UTILIZATION

A Section of SwRI

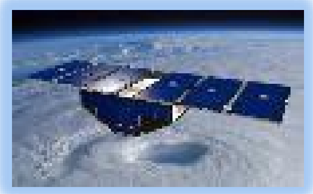
SwRI® Technical Expertise

- Applied Physics
- Applied Power
- Chemistry and Chemical Engineering
- Defense and Intelligence Solutions
- Fuels and Lubricants Research
- Intelligent Systems
- Mechanical Engineering
- Powertrain Engineering
- Space Science
- Space Systems
- Solar Systems Science

"Deep Sea to Deep Space"

And Everything Between

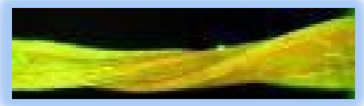

Energy


Cyclone Forecasting


Homeland Security, Defense, and Intelligence


Robotics, Automation, and Simulations


Drug Discovery


Regenerative Medicine

Infrastructure Communications


Alvin Deep Diving Submersible


Water and Geological


Engine Design and Optimization

SwRI® Technical Expertise

- Applied Physics
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- Defense and Intelligence Solutions
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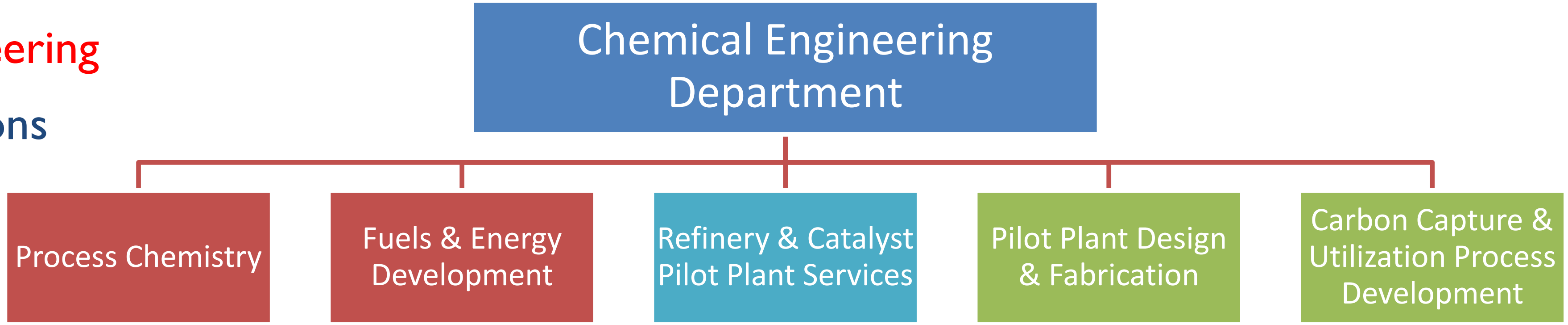
- Powertrain Engineering
- Space Science
- Space Systems
- Solar Systems Science



Carbon Capture and Utilization Process Development (CCU-PD)

CO_2 Capture

Point Source Capture – Pilot Units

- CO_2 to Carbonates
- CO_2 flue gas separation

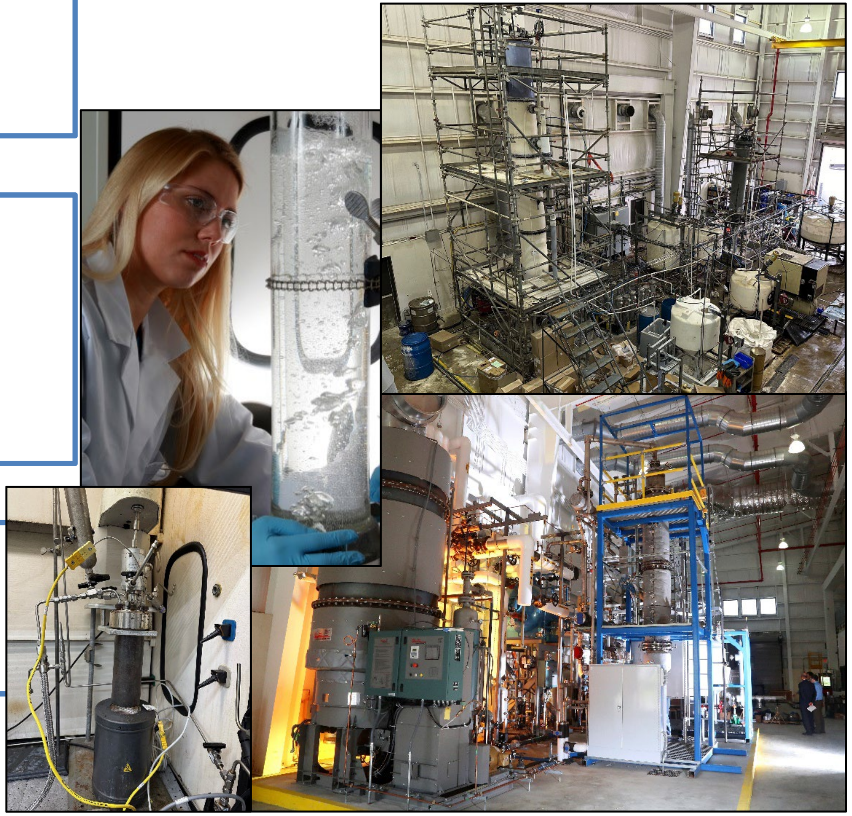
Lab Testing

- VLE Testing Capabilities
- Absorption/Desorption Kinetics
- Sparger Design
- Analytical Characterization

Engineering Services

- TEA of value-added product streams
- Pilot to Demonstration scale testing

CO_2 Market



CO_2 Utilization

CO_2 Market Areas

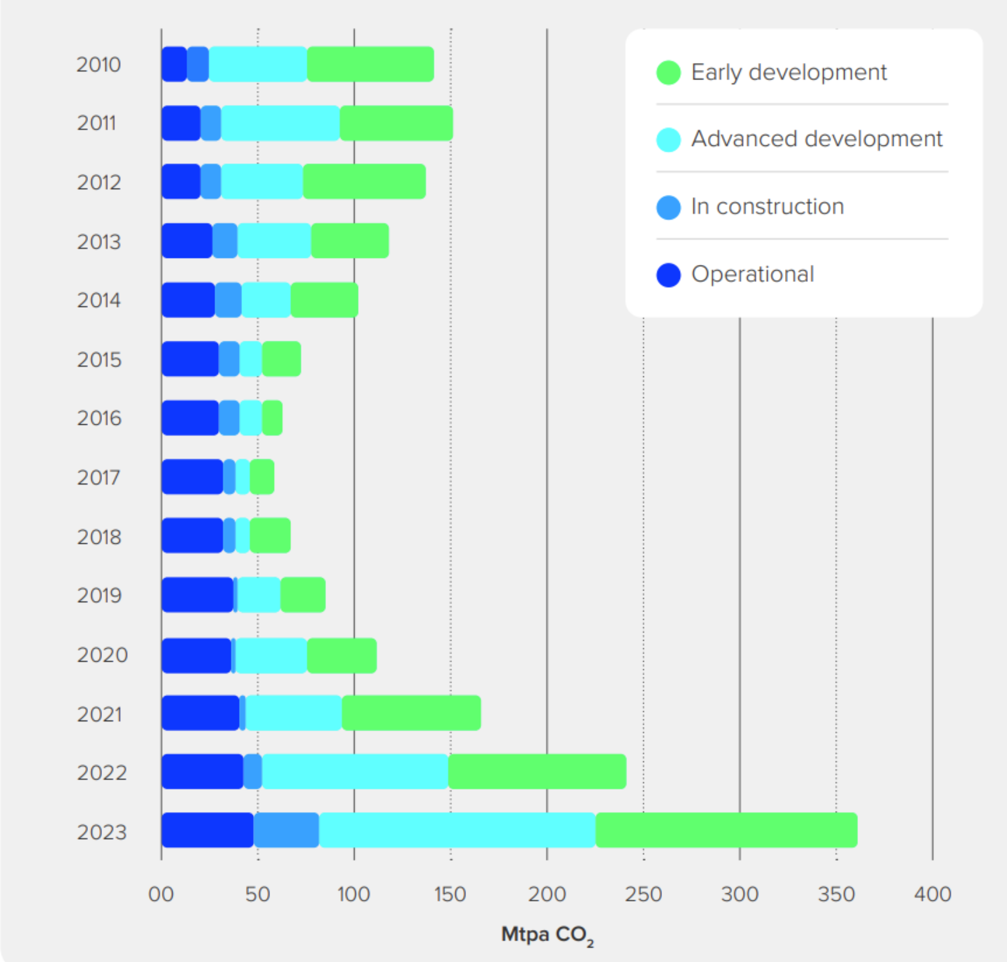
- CO_2 to Fuels (RWG/FTS)
  - Sustainable Aviation Fuel (SAF)
- CO_2 to Chemicals
  - Methanol, olefins, aromatics
- CO_2 to Polymers
  - Plastics, foams, resins

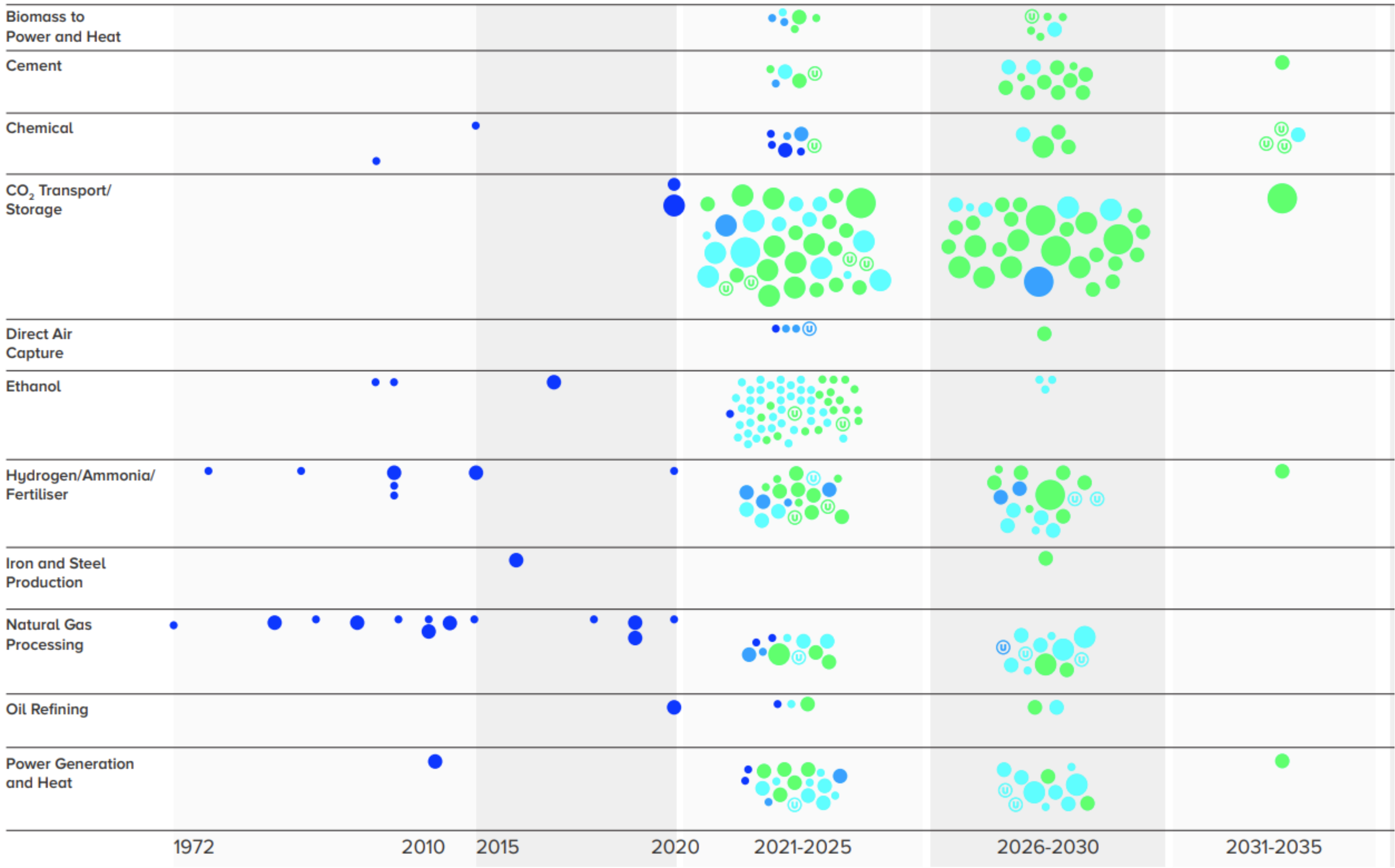
CO_2 to Value-Added Products

- Consider CO_2 as valuable starting material for new and emerging markets
- Support R&D and new technology development such as graphene generation

Global CCUS Trends

Figure 3.1–1: Capacity of commercial facility pipeline since 2010

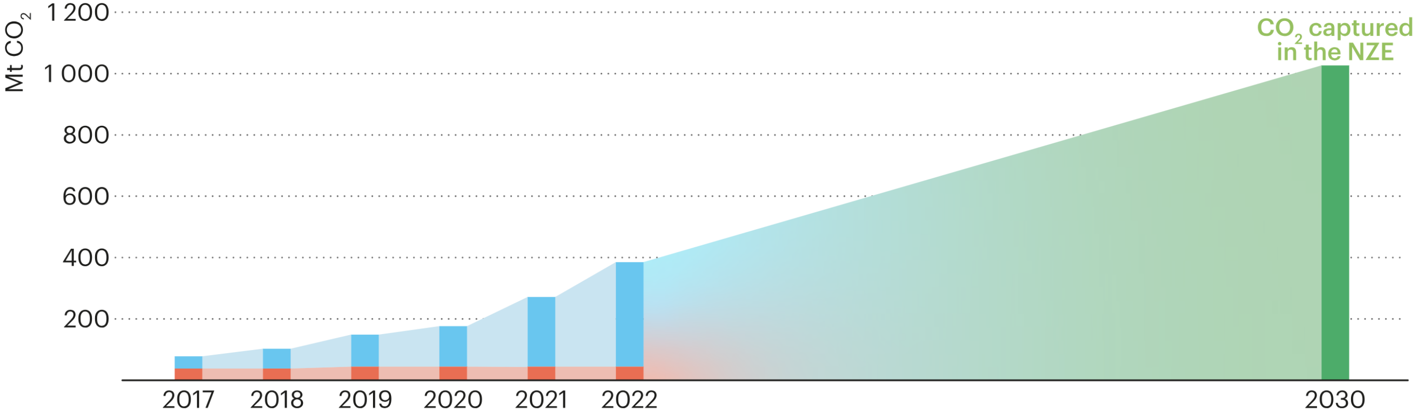




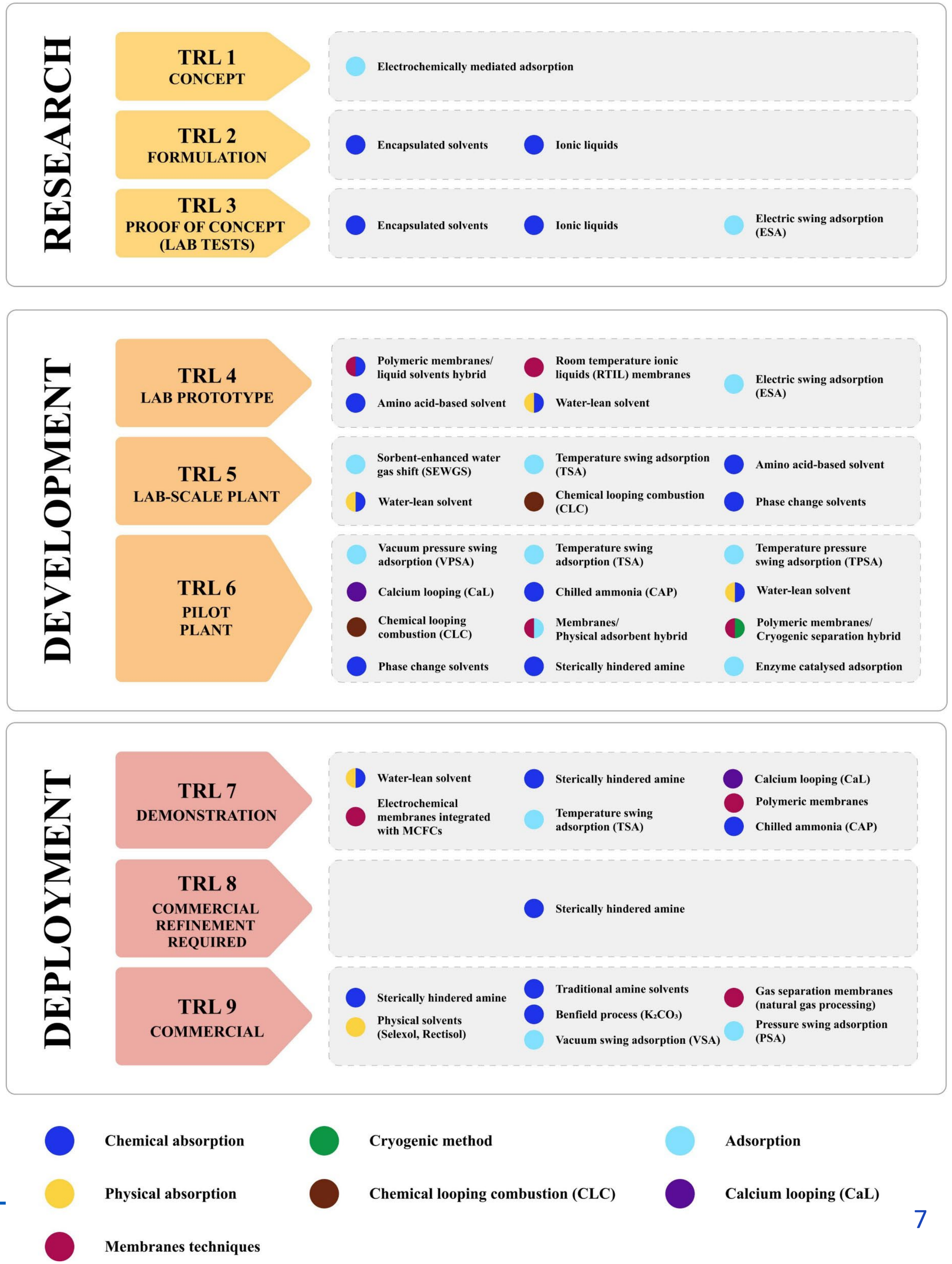
Global-Status-of-CCS-Report-1.pdf (globalccsinstitute.com)

CO_2 Capture

- Commercialized technology [TRL 7-9]
  - Amines, PSA, VSA
- Room for improvements [TRL 1-6]
  - Absorption capacity
  - Selectivity
  - Energy reduction



CCUS – Analysis - IEA



https://doi.org/10.1016/j.fuel.2023.127776

CO_2 Capture – Deployment

Technology	Advantages	Disadvantages
Amines	• High absorption efficiency (>90%) • Regenerative sorbents • Mature Process • Designer amines	• Absorption dependent on CO2 concentration (partial pressure) • Regeneration requires large amounts of thermal energy • Sorbet degradation (environmental) • Solvent loss • Selectivity • Requires feed gas cooling
PSA/VSA/TSA	• High selectivity (PSA at higher pressures) • High purity (99%) and high recover (>90%) • VSA – lower pressure operation, humid environments	• Requires pure flue gas (remove H_2O, NOx, SOx) • Regeneration cycles • Sorbent loading (size of equipment) • Sorbent material degradation
Calcium Looping **-CFB, Carbonator and Calciner** **-CaO + CO_2 ←→ $CaCO_3$** **Carbonation: 550-700C** **Calcination: 800-950C**	• Can handle high temperature feed gases • Regenerative sorbents • Can handle impurities (CO, H_2, CH_4) • High capture efficiencies (>90%) at low partial pressures	• Requires high energy for calcination • Reaction efficiency can become mass transfer limited • Deactivation over time

Air Liquide/BASF [85 units], 150-5000 tpd

Linde/Honeywell/Air Liquide [1150 units], 10-5000 tpd

Calcium Looping 1.7 MW demo plant completed in La Pereda, Spain. The pilot plant was commissioned in 2012 with demonstrated capture efficiency of over 90%

Sumitomo, >50 tpd
Tecnicas Refundias (V-CAL)
8-Rivers (Calcite)

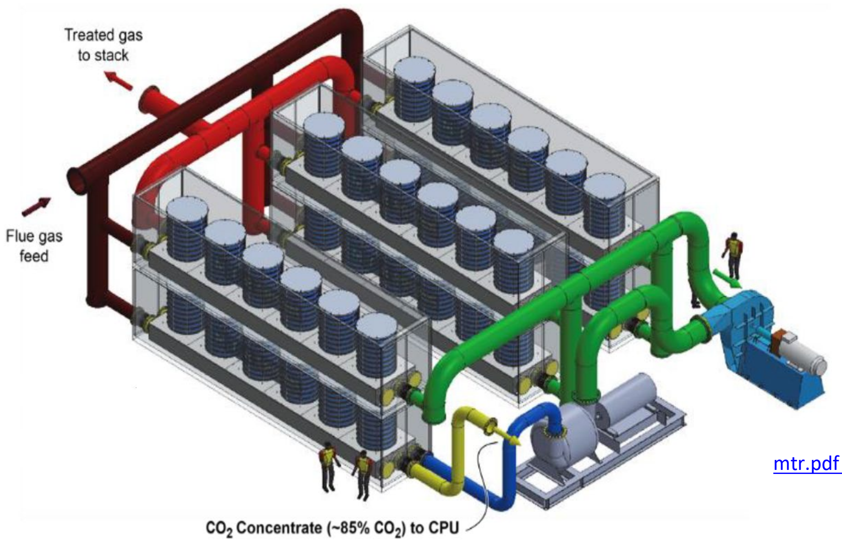
Report-CCS-Technologies-Compendium-2024-3.pdf (globalccsinstitute.com)

CO_2 Capture - Development

Technology	Advantages	Disadvantages

Polymeric Membranes
• Solution-diffusion
  • Polyethylene Oxide (PEO),
  • Perfluro
  • Thermally rearranged (TR)
• Facilitated Transport
  • Amine based
	• Smaller footprint
	• Reduced energy
	• No phase transformation
	• Reduced operating cost (simple system)
		• Permeability and selectivity trade-off
		• PEO – crystallinity/film-forming
		• Relatively low temperature

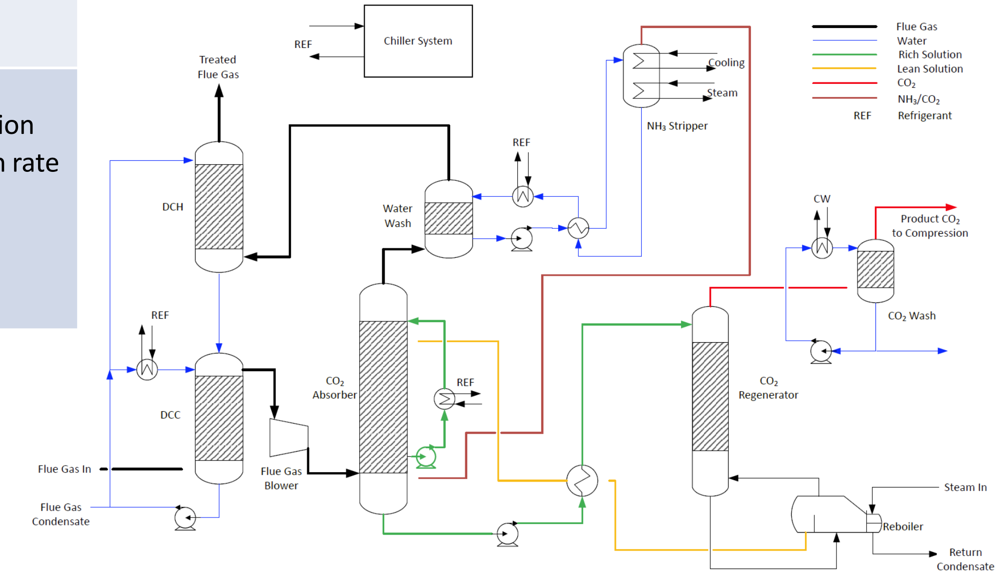
Ceramic Membranes • Air Products/DOE • SwRI-Li_2ZrO_3 based	• Thermal stability • Mechanical stability • Small footprint • Elevated temperature operation • Reduced operating cost	• Production cost • Seals/leakage
Chilled Ammonia • Baker Hughes	• Absorption at high loading (1.0 mol-CO_2/mol-NH_3 – MEA is 0.5 mol) • Low corrosion • Low degradation • Easy regeneration	• Ammonia escape • Secondary pollution • Lower absorption rate



mtr.pdf (mtrinc.com)

200 tpd pilot - Polaris Membrane - 10x CO_2 permeance, 10x size reduction

Baker Hughes, Chilled Ammonia Process

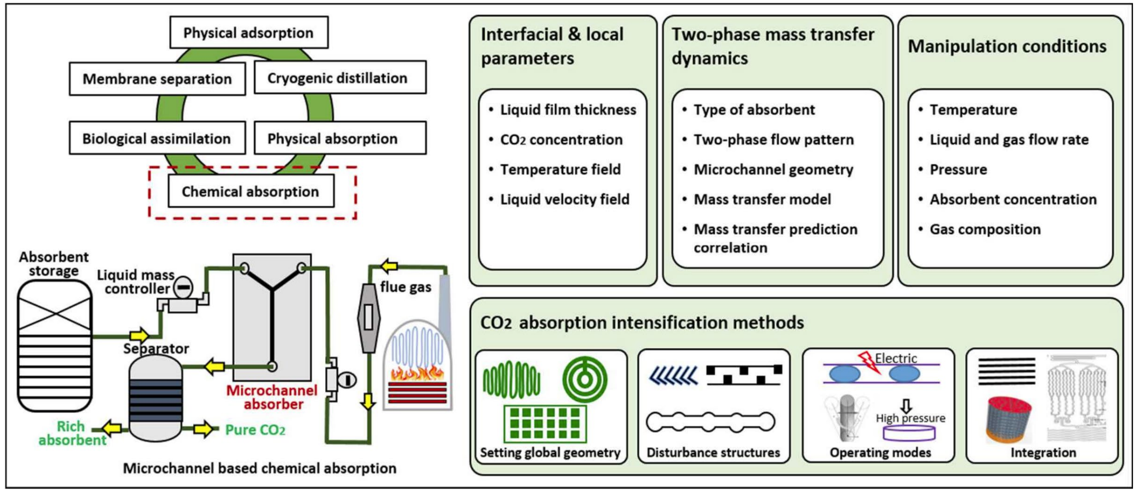


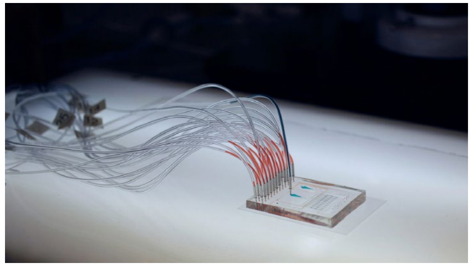
Report-CCS-Technologies-Compendium-2024-3.pdf (globalccsinstitute.com)

CO_2 Capture - Research

Technology	Advantages	Disadvantages
Ionic Liquids • Room temperature molten salts composed of cations and anions • Supported Ionic Liquids (SILs) • Encapsulated solvents	• Low volatility • High tunability	• Increase in viscosity after CO_2 capture • High cost
Electrcoswing Adsorption (ESA) • Flow gas • Activate electrodes • Capture CO_2 • Deactivate electrodes • Release CO_2	• Reduced energy consumption (electrical versus thermal) • Reduced overall cost • Reduced footprint	• Requires "Green" grid • Requires conductive adsorbents • Requires even heating • Requires significant time to cool (Heating is ~1.5% of cycle time)

Microfluidics for CO_2 Absorption/Conversion





Protic Ionic Liquid (PILs)

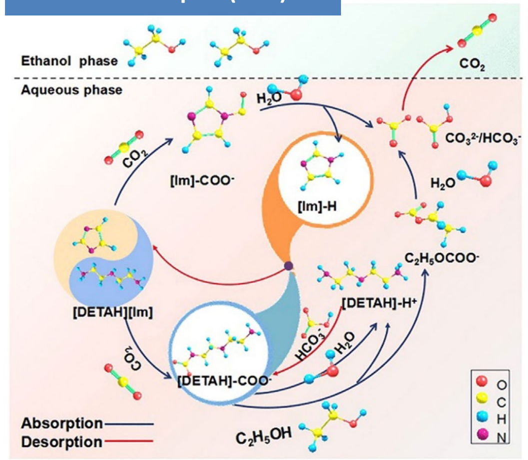
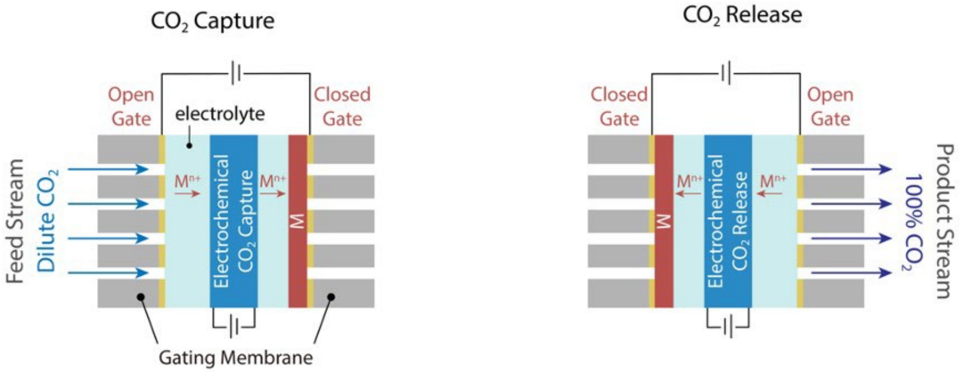


Fig. 3.6. The mechanism of CO_2 capture into [DETAH][Im]-EtOH-H_2O (Lü B, 2021). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

https://doi.org/10.1016/j.ccst.2023.100178.

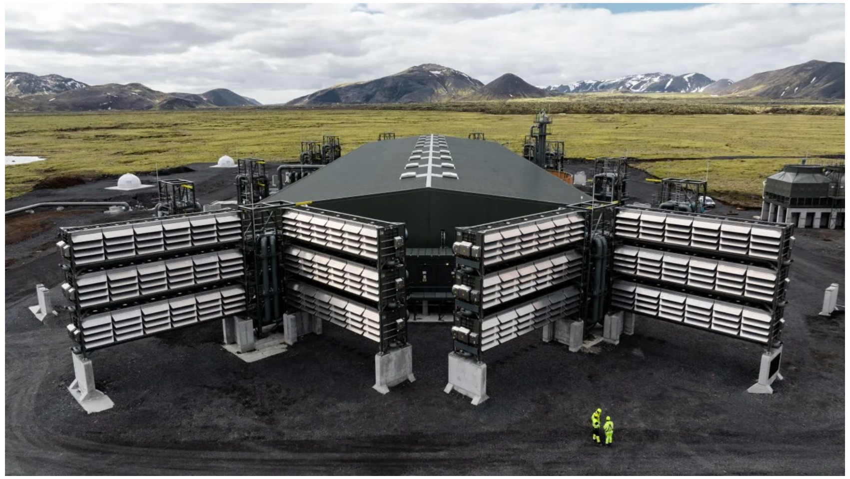
Electroswing Adsorption



Electro swing direct air capture - Advanced Science News

CO_2 Capture – DAC (In Between)

- DAC Systems
  - Multi-technology
    - Adsorption, absorption
    - Liquid, solid media
  - Low CO_2 concentration
  - Typically, in dry environments
- Challenges:
  - Cost
    - Size required, first of kind units
  - End use of CO_2
    - On site usage
    - Pipeline to EOR / sequestration

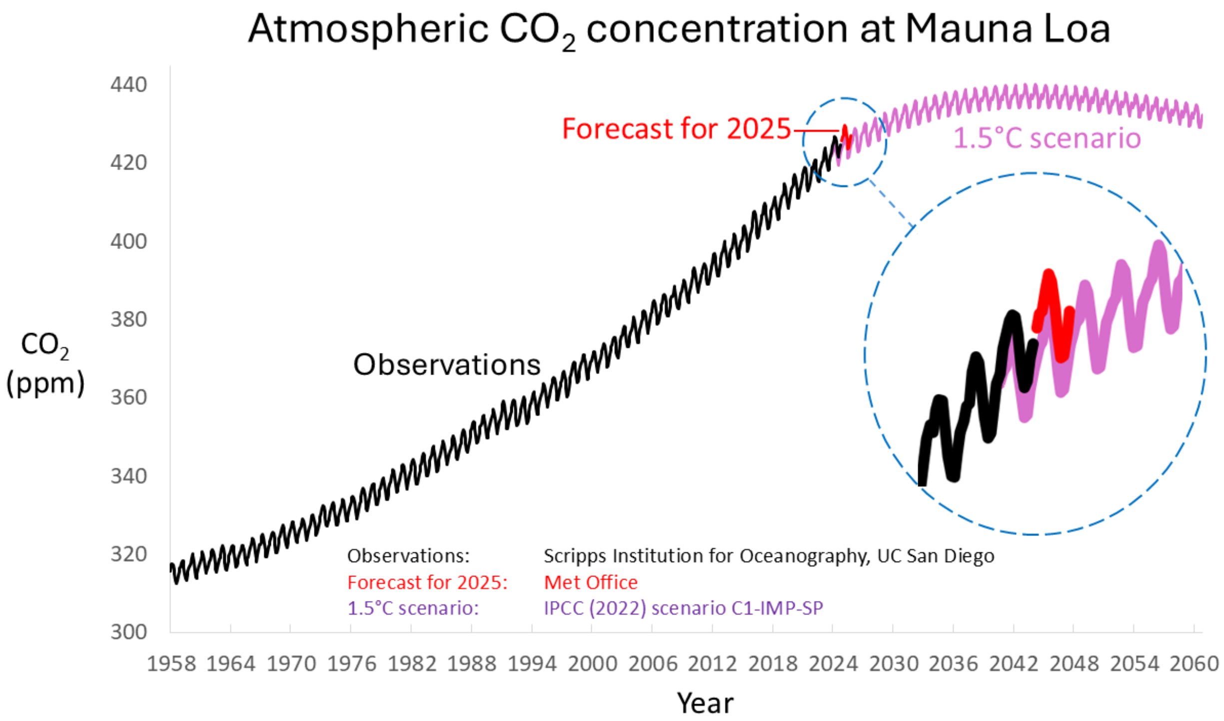


Climeworks – Mammoth, Iceland: 36,000 tons/yr

1Pointfive (CarbonEngineering/Oxy) – STRATOS, West Texas: 500,000 tons/yr

CO_2 Capture R&D Drivers

- Optimize solvent/column technology
  - Increase absorption capacity
  - Reduce regeneration energy
  - Increase lifetime
  - →Reduce opex
- Reduce capex
  - Smaller footprint
  - Reduced size
- New Tech Development
  - Innovation



Mauna Loa carbon dioxide forecast for 2025 - Met Office

CO_2 Transport (pipelines)

- US:
  - 5000 miles of CO_2 pipeline
  - 260,000 hazardous liquid pipeline
  - 3-million natural gas pipeline

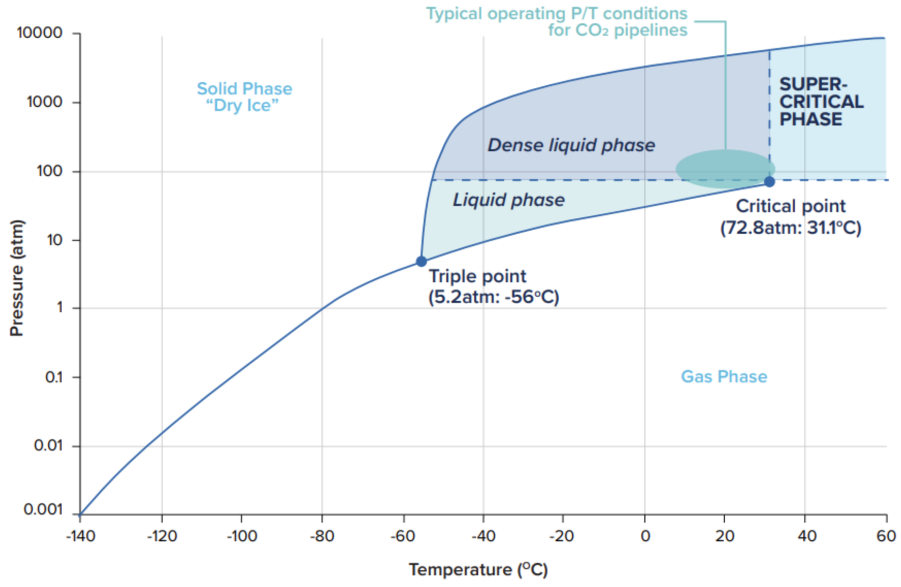


Figure 6. Carbon dioxide phase diagram (after Mazzoldi et al., 2008). Dense phase CO_2 includes both dense liquid phase CO_2 and supercritical CO_2. CO_2 is typically transported in its dense liquid phase (circled region in the figure).

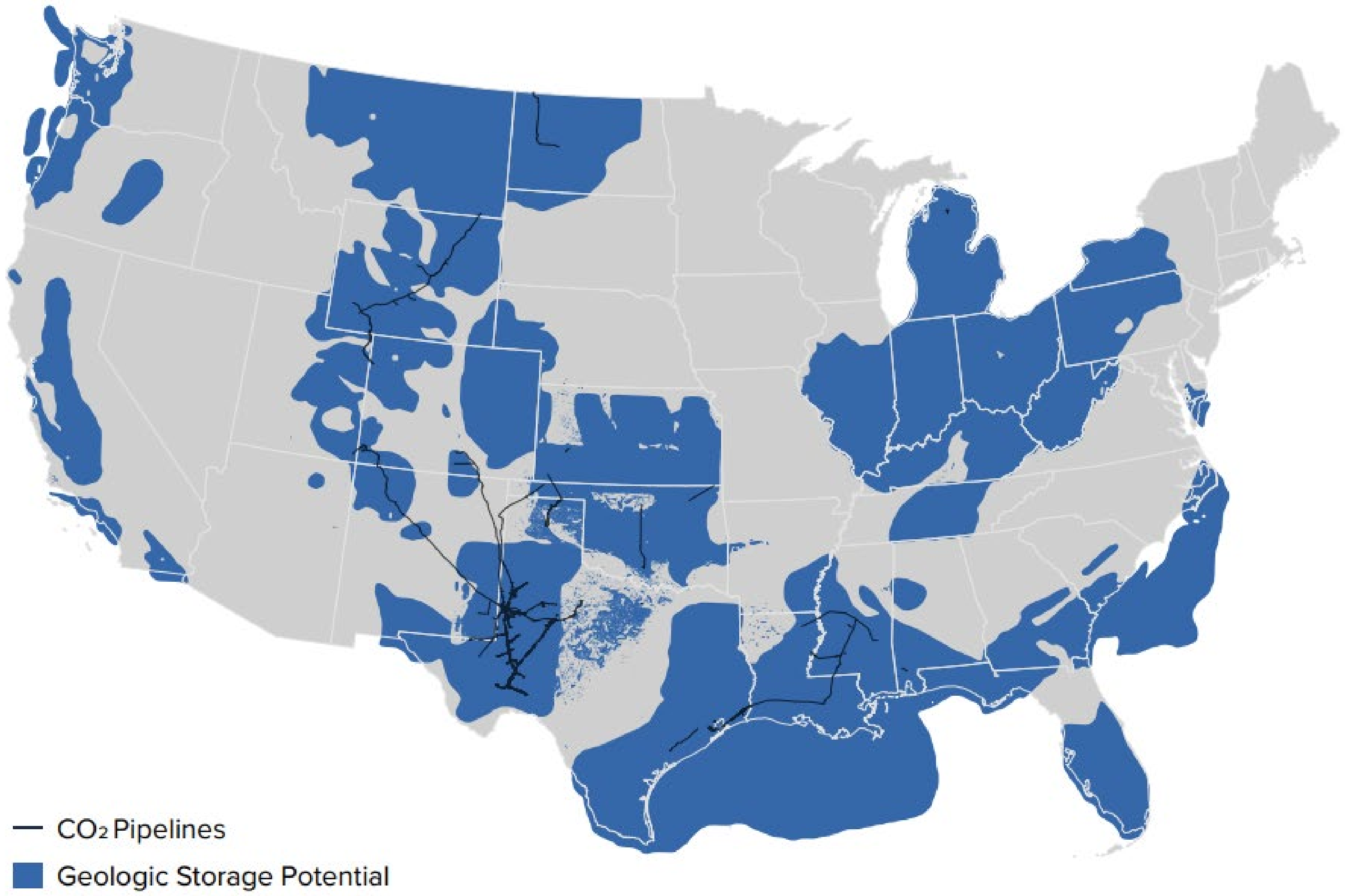
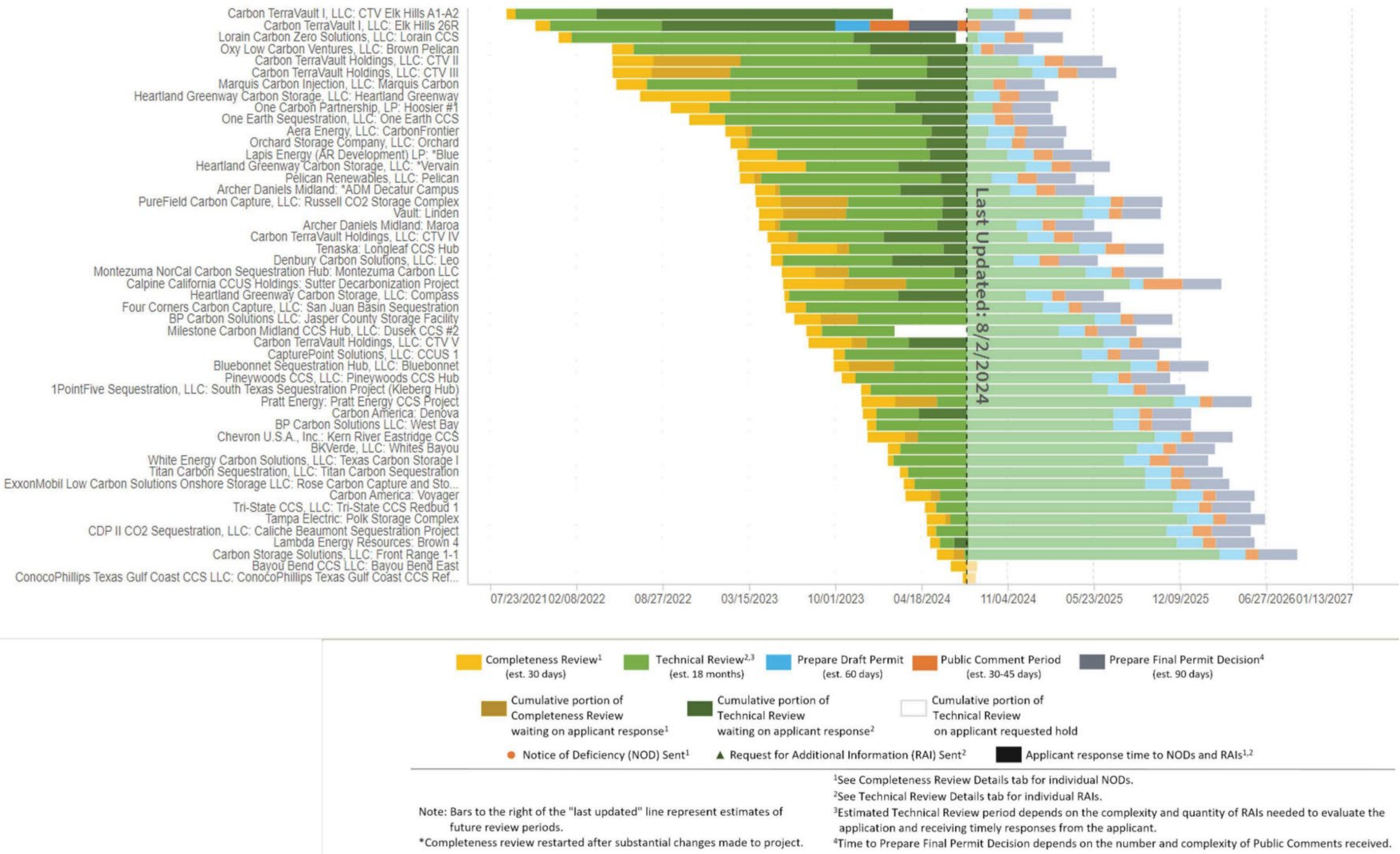


Figure 4. CO_2 pipelines and geologic storage potential in the US. (Storage regions from the National Carbon Sequestration Database and Geographic Information System, NATCARB. Figure courtesy of the Great Plains Institute.)

Building-Our-Way-to-Net-Zero-Carbon-Dioxide-Pipelines-in-the-United-States.pdf (globalccsinstitute.com)

CO_2 Sequestration

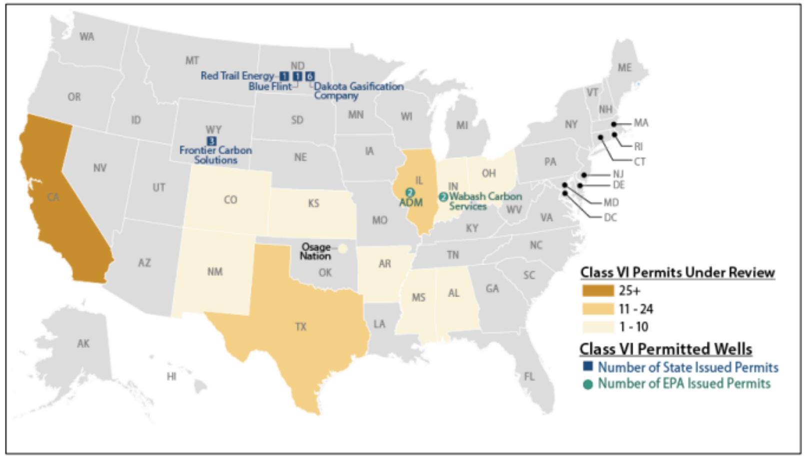
UIC Class VI Permit Tracker



[Current Class VI Projects under Review at EPA | US EPA]

- EPA: 8-permits (Illinois/Indiana)
- Primacy States:
  - North Dakota: 8
  - Wyoming: 3
  - Louisiana: 0
- 130+ EPA permits pending

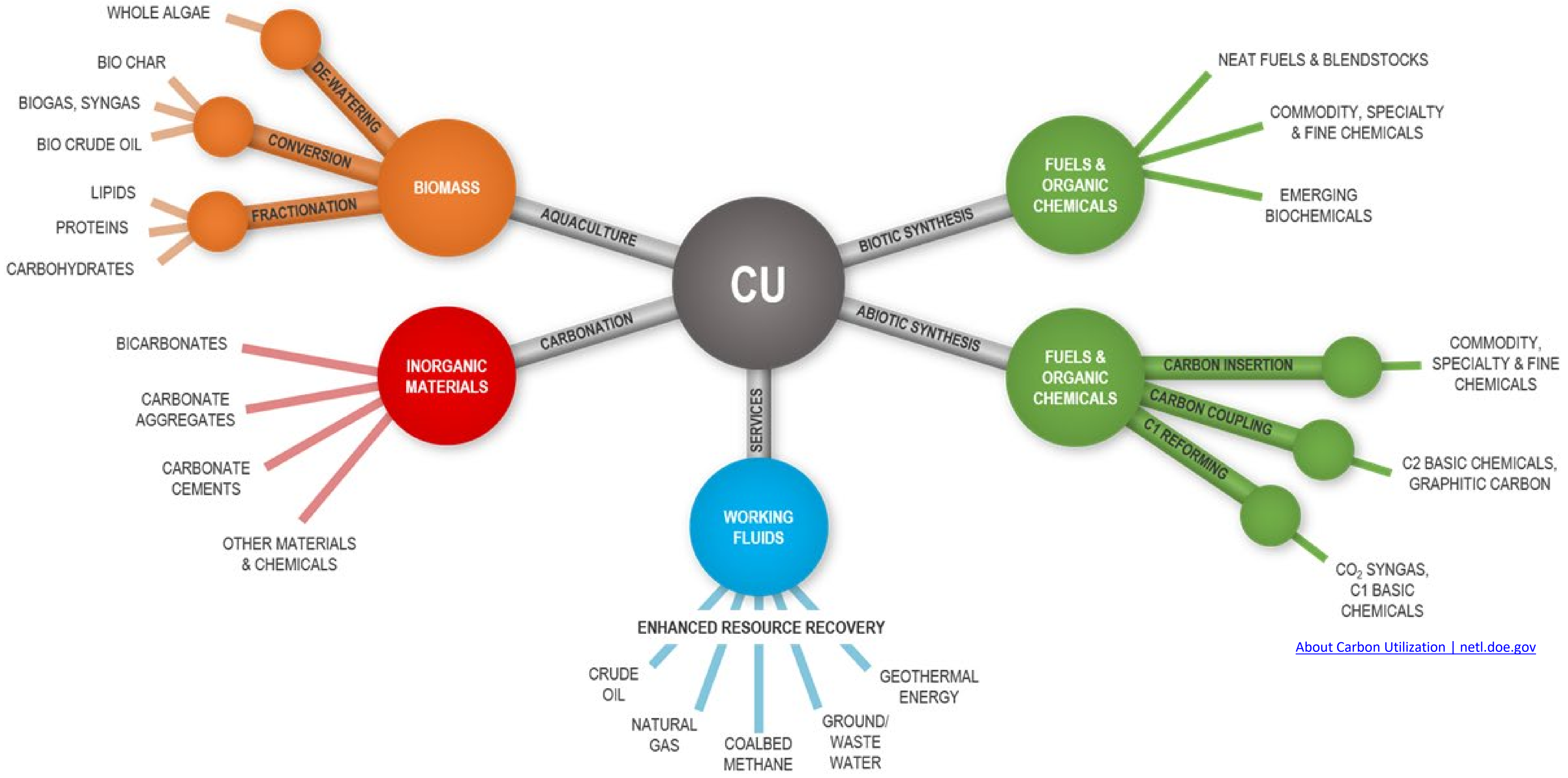
Figure 1. Class VI Permits Issued and Under Review by EPA



Source: CRS graphic based on U.S. Environmental Protection Agency, "Current Class VI Projects Under Review at EPA," accessed on April 1, 2024, https://www.epa.gov/uic/current-class-vi-projects-under-review-epa.

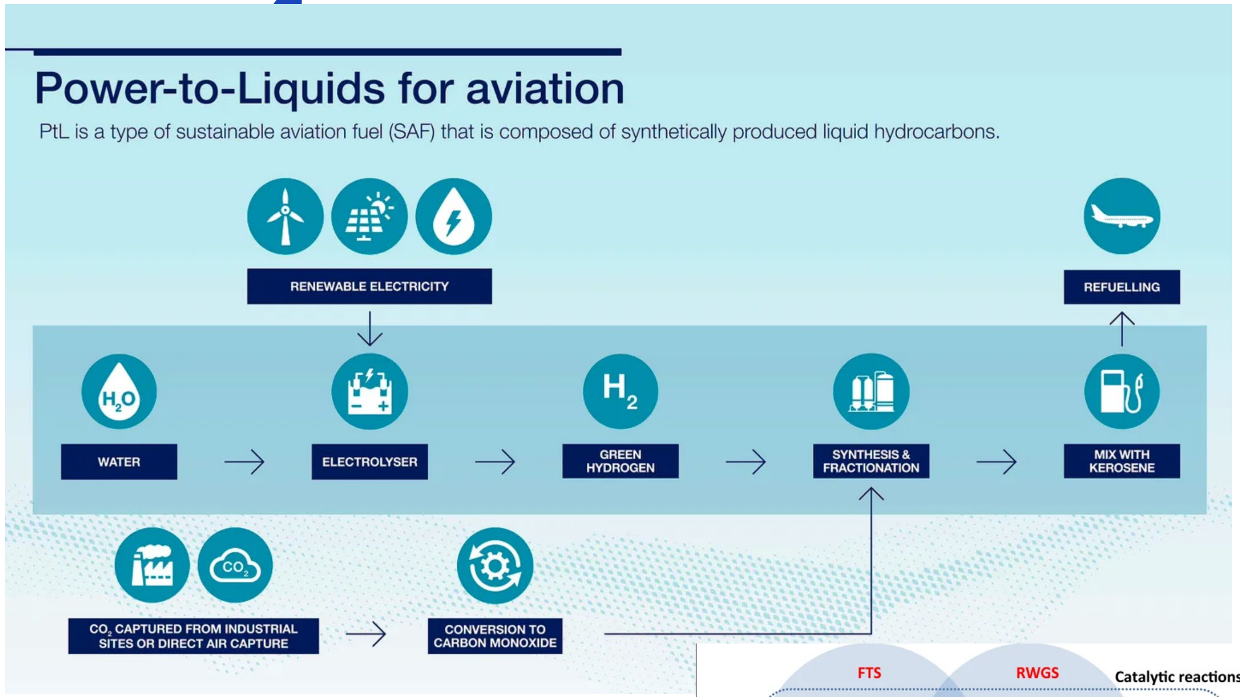
Note: Figure includes permits under review by EPA as of April 1, 2024. Figure does not include permits that may be under review by states with UIC Class VI program primacy, as these are managed by individual states rather than EPA.

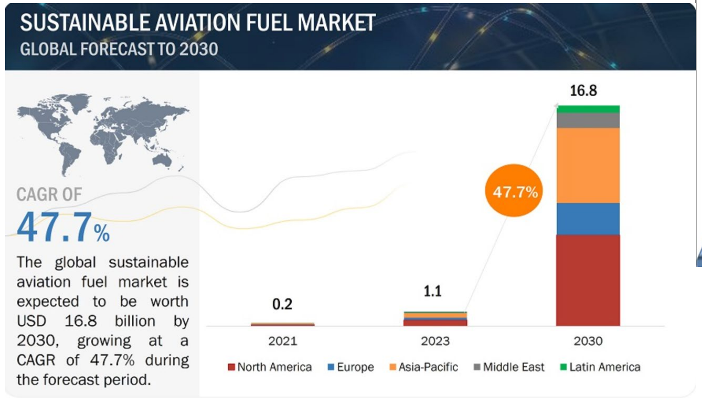
CO_2 Utilization

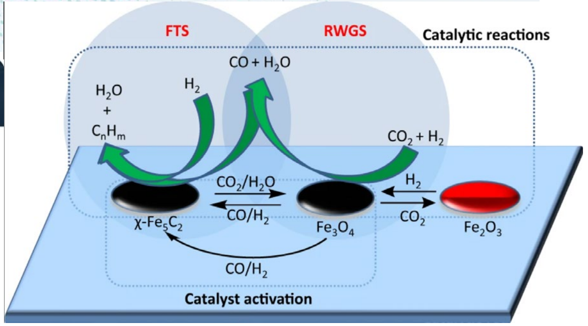


About Carbon Utilization | netl.doe.gov

CO_2 Utilization - Fuels





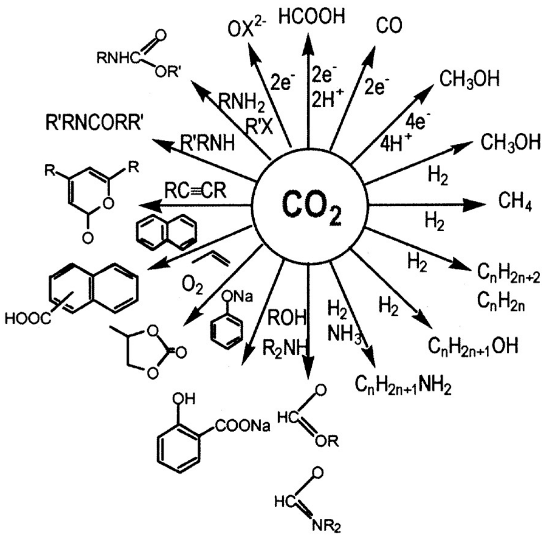


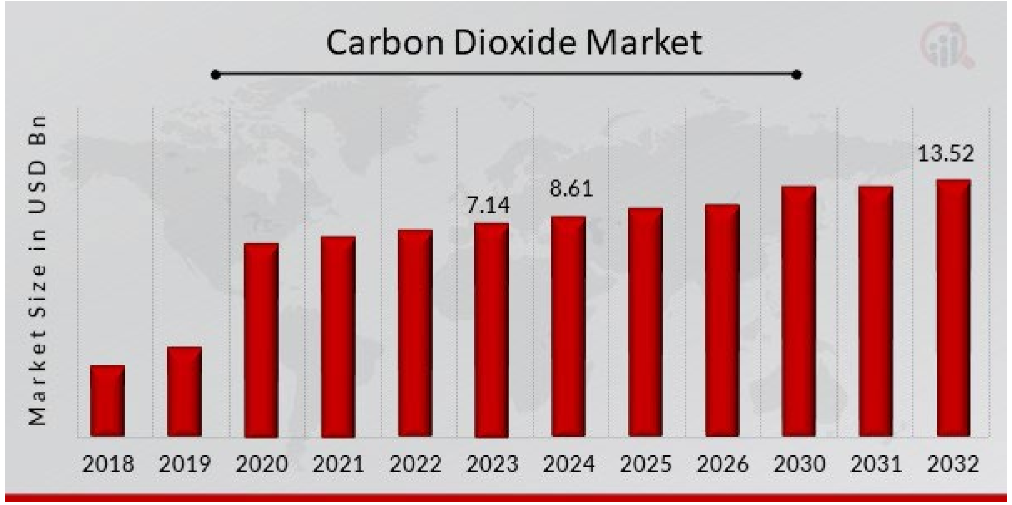
2 – 100 mL reactors

20L, 7L, & 3L reactors

CO_2 Utilization – Chemicals / Building Materials

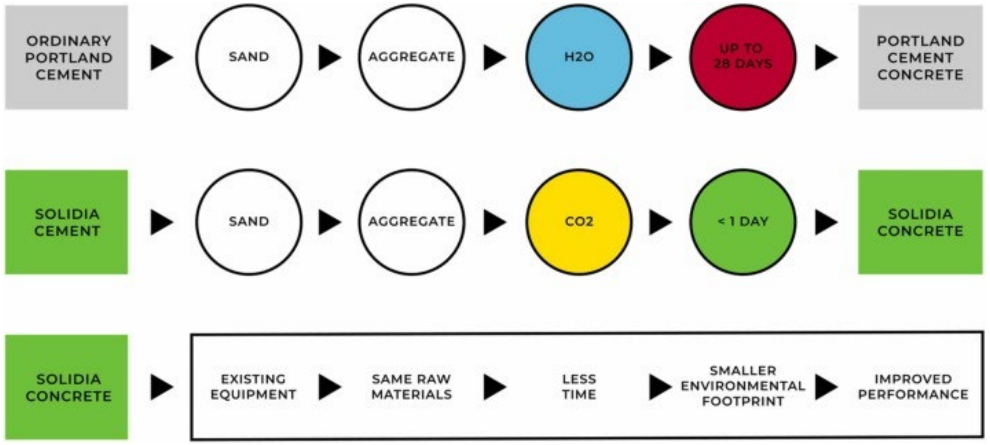
- Intermediate of fine chemicals for the chemical industry
  -C(O)O-: Acids, esters, lactones
  -O-C(O)O-:Carbonates
  -NC(O)OR-: Carbamic esters
  -NCO: isocyanates
  -N-C(O)-N: Ureas
- Use as a solvent
- Energy rich products
  CO, CH_3OH



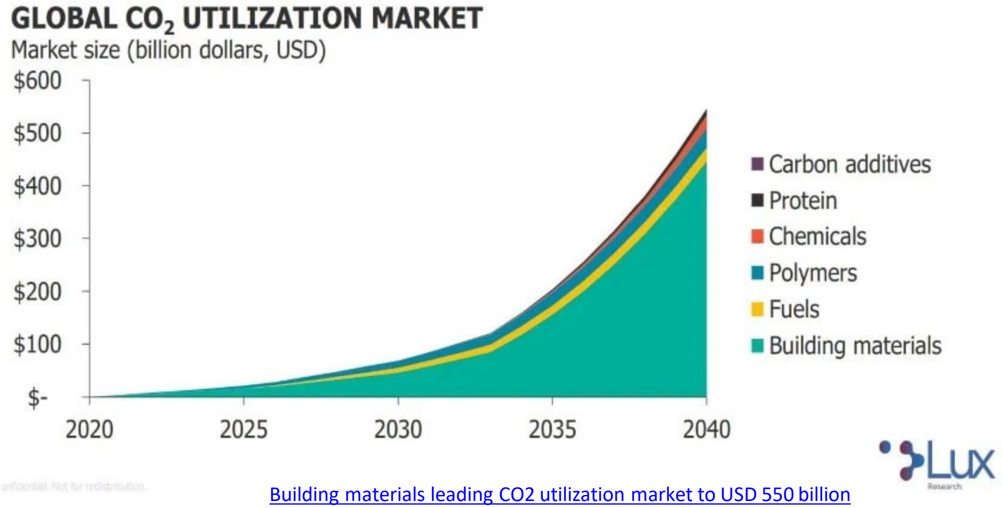


5. Carbon Dioxide as a Feedstock | Carbon Management: Implications for R&D in the Chemical Sciences and Technology | The National Academies Press

Carbon dioxide Market Size, Share & Forecast Report 2032 (marketresearchfuture.com)



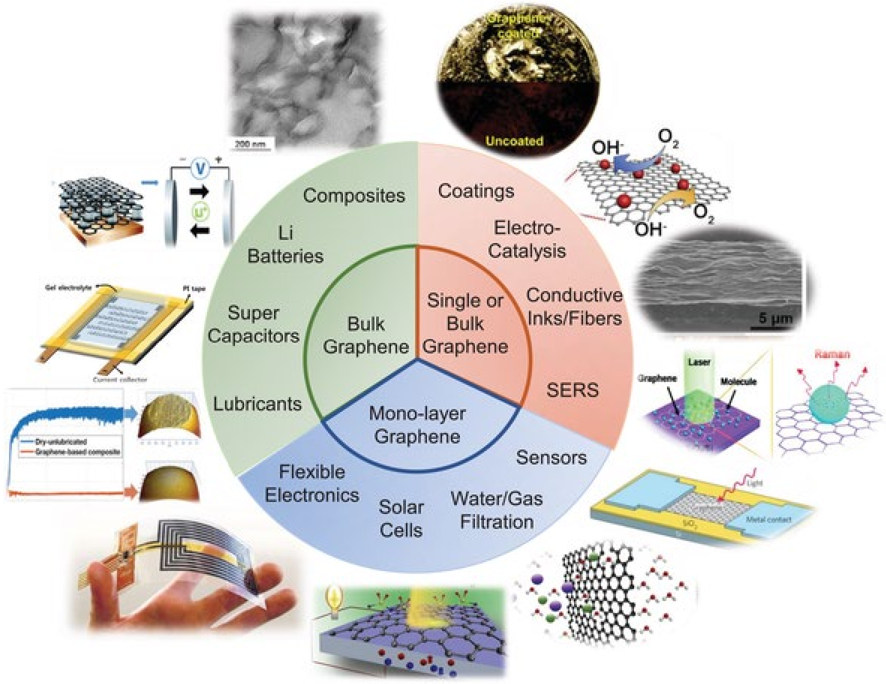
Emerging CO2 utilization technologies for construction materials: A review - ScienceDirect



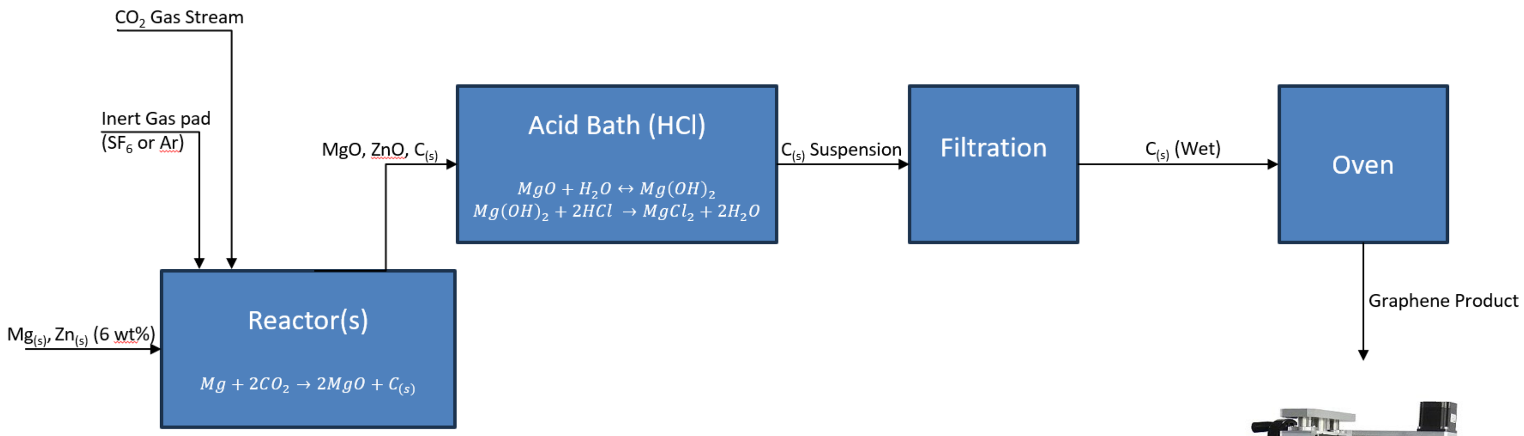
Building materials leading CO2 utilization market to USD 550 billion

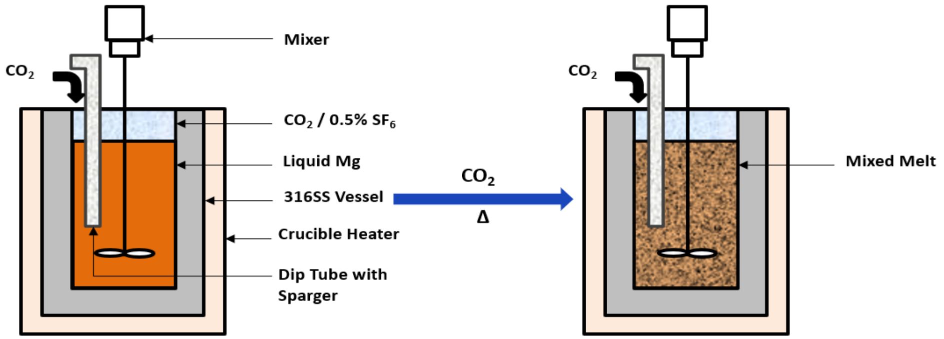
CO_2 Utilization – Novel Markets

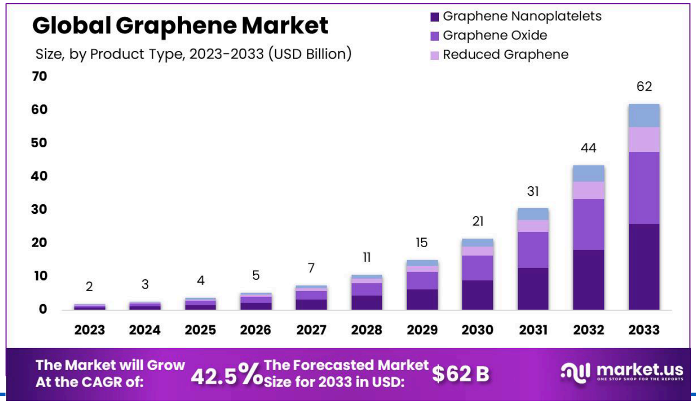
- CO_2 to Graphene
  - SwRI IRD - Magnesiothermic Reduction



Kevin Wyss, D. X. (2022). Large-Scale Syntheses of 2-D Materials: Flash Joule Heating and Other Methods. Advanced Materials , 34



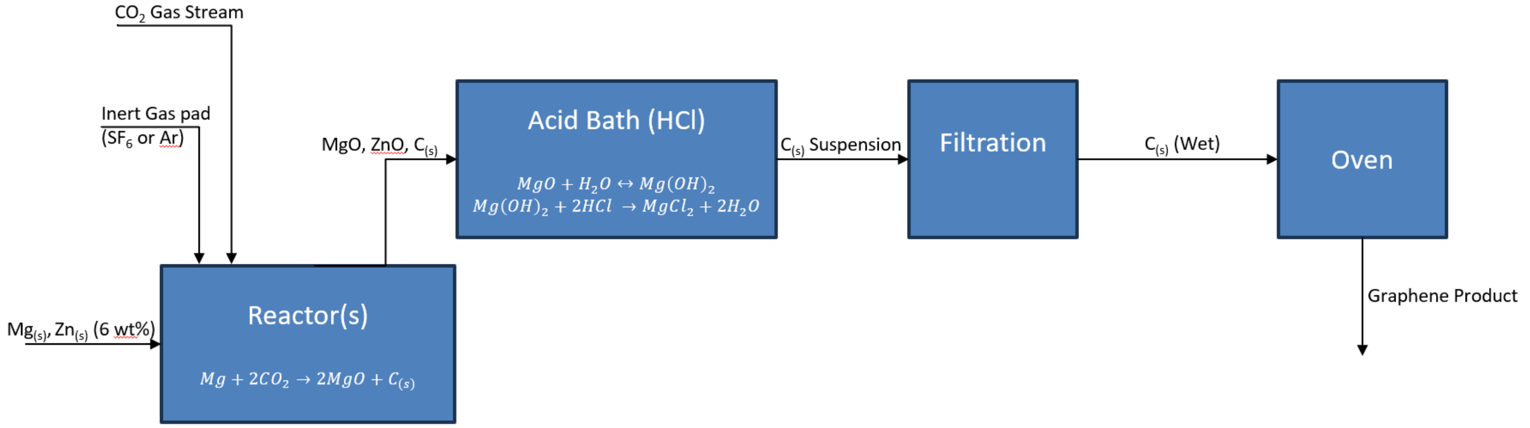


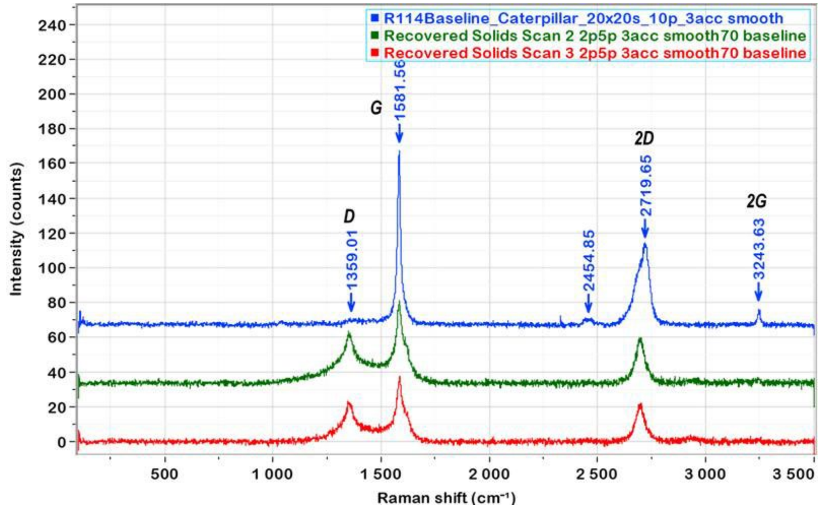


Graphene Market Size, Share, Trends | CAGR of 42.5%

CO_2 Utilization – Novel Markets

- CO_2 to Graphene
  - SwRI IRD - Magnesiothermic Reduction
- Results so far
  - Increased yield
  - Increased dispersion
- Next steps
  - Complete test matrix
    - Higher conversion
    - Increased quality
  - Perform TEA for larger system
  - Scaleup (g → kg scale)





[Graphene Market Size, Share, Trends | CAGR of 42.5%]

Role of R&D

Increase TRL level	→ Lab to pilot development [TRL 3-7] → Bridge "valley of death"
Piloting novel technologies	→ Learn at smaller scale (lower $ value for process changes) → Batch to continuous
Continue pipeline of new tech	→ Innovative and disruptive technologies
Gov/Industry Bridge	→ Using government programs to advantage

Closing

- CO_2 is an emerging market
  - CO_2 utilization has historically had minimal growth (demand constant)
  - See increase with CO_2 availability in market
- CO_2 capture is "Standardizing"
  - General tech is simple/mass produceable
- Role of government
  - Important but less reliant
- Role of R&D
  - Key to innovation and improvements
  - Identifying new market areas
  - Reduced cost of learning mistakes ($)

Thank you

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CARBON CAPTURE AND UTILIZATION

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