Perspectives on the Future of Carbon Capture Technology

CCUS and Hydrogen Symposium

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Heterogeneity of CO_2 Sources

Category	% CO_2 (vol)	Example
High Pressure	varies	Gas Wells (e.g., Sleipner) Synthesis Gas (e.g., IGCC)
High Purity	90-100%	Ethanol Plants Oxy-Combustion Exhaust
Dilute	10-20%	Coal-Fired Power Plants Cement Plants Cracker Exhaust
Very Dilute	3-7%	Natural Gas Boilers Gas Turbines
Extremely Dilute	0.04 – 1%	Ambient Air Submarines/ Space Craft

History of CO_2 Capture

- December 2, 1930 – R. R. Bottoms patent
- 1978 – Trona plant (CA) – amines first applied to flue gases
- 1980s/1990s - Small scale capture from flue gases
  - Drivers included oil shocks, PURPA
- 1982 to present - Large-scale capture for EOR
  - Sources include natural gas (NG) processing, fertilizer plants, and coal gasification
- 1996 to present - CCS Megatonne Demos
  - Driver is climate change
  - Sectors include power, hydrogen, ethanol, steel

Capture Technology

- State-of-the-Art today for dilute feeds
  - Chemical scrubbing with amines
- Alternatives
  - Other post-combustion technologies
    - » Membranes, Adsorption, Cryogenics, Fuel Cells, etc.
  - Other approaches
    - » Oxy-combustion, Chemical looping, Gasification with pre-combustion, etc.

“I Hate Amines”
Amit Chakma, ICCDR-1, 1992

- Dislike Impurities
  - Foaming
  - Degradation
- Emissions
- Require Steam
- Energy Intensive

Approaches to Lower Cost CO_2 Capture

Strategy	Positives	Limitations
New/Improved Solvents	High probability of success	Evolutionary change, not revolutionary
New Materials and Processes	Many potential ideas	Low probability of success for any given project
New Processes to make capture easier	Potential for significant cost reductions	Development will be long, expensive, and risky

New Materials and Processes Examples

- Molten Carbonate Fuel Cells (FuelCell Energy/ExxonMobil)
- Cryogenics (SES Innovation)
- Membranes (Membrane Technology and Research (MTR))
- Others
  - Electrochemically Mediated Separation
  - Metal-Organic Frameworks
  - Biological Catalyst
  - Phase-Changing Absorbents
  - Ionic Liquid

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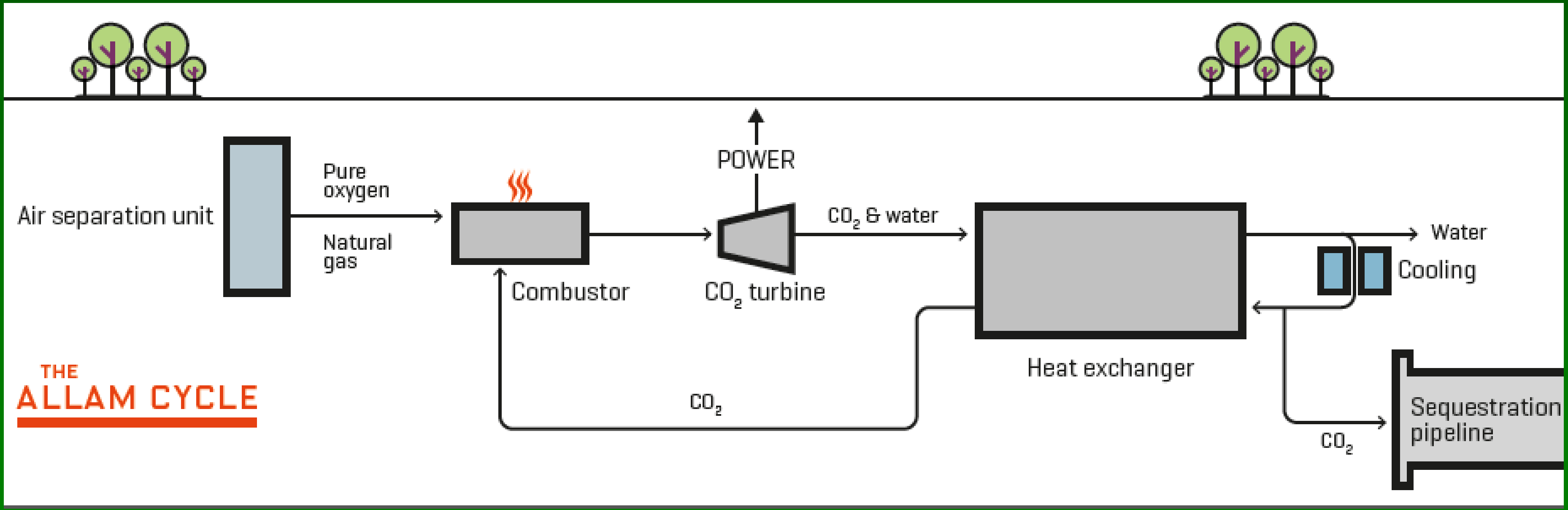
New Processes Example
Allam Cycle

- Net Power -- 8 Rivers, McDermott, Exelon, Oxy Low Carbon Ventures, and Toshiba
- 50 MW_{th} prototype near Houston
- Turbine inlet: 300 bar, Turbine outlet: 30 bar, ~97% recycle



National Petroleum Council

Meeting the Dual Challenge:
A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage

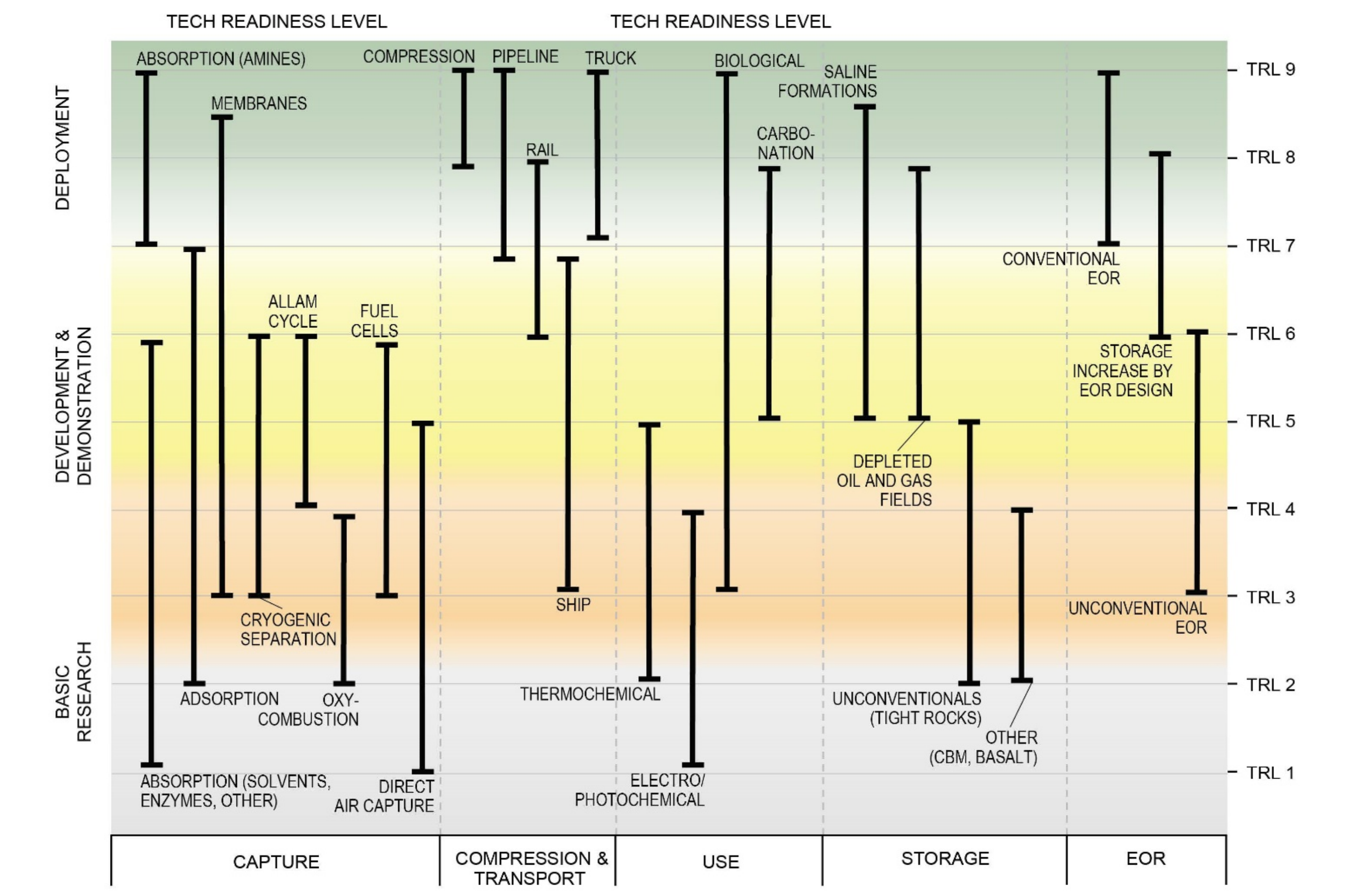


Figure ES-18. Technology Readiness Level Ranges for CCUS Technologies

https://dualchallenge.npc.org/

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Research Focus

- Main focus to date has been to reduce the energy penalty
- The following are becoming increasingly important:
  - Flexibility
  - Energy storage
  - Low capital costs

Recent Trends

- Baseload Power Model is changing
- Higher capture efficiencies desired
- Interest beyond power sector
  - Industry
  - Hydrogen
  - Negative Emissions
    - » Bioenergy with CCS (BECCS)
    - » Direct Air Capture (DAC)

Industry

- Seven largest industries, including cement, iron & steel, and chemicals, account for ~20% of global CO_2 emissions
  - Predicted growth of 35% by 2050
- Significant percentage of CO_2 emissions from process, not energy
  - Only about a 30% reduction can be obtained via efficiency improvements and use of non-carbon energy sources

Hydrogen

- Least cost pathway for hydrogen production today is Steam Methane Reforming (SMR) of natural gas
  - Cost very sensitive to natural gas price
  - In US today, electrolytic hydrogen costs ~4 times as much to produce as SMR hydrogen
- Least cost pathway to low-carbon hydrogen is SMR with CCS ("blue hydrogen")
  - Demonstrated at the million ton CO_2 per year level at Air Products (Port Arthur, TX) and Shell Quest (Alberta, Canada)

Cost of Hydrogen Production

	Japan		US	
	$/kg	Relative to Grey	$/kg	Relative to Grey
Grey (SMR)	1.49	1	0.87	1.0
Blue (SMR w/CCS)	2.20	1.5	1.52	1.8
Green (PEM)	12.62	8.5	5.28	6.1

Natural Gas Prices: Japan $7.5/MMBtu, US $3.53/MMBtu
Electricity Prices: Japan $206/MWh, US $70/MWh

Capture from Hydrogen Production

- Three potential capture points
  - Syngas outlet (also referred to as PSA inlet)
    - CO_2 concentration ~15-16%
    - Pressure ~22-23 bar
    - ~60% capture achievable
  - PSA Tail Gas
    - CO_2 concentration ~45-50%
    - Pressure ~1.3 bar
    - ~55% capture achievable
  - SMR Flue gas
    - CO_2 concentration ~19%
    - Pressure 1 bar
    - ~90+% capture achievable
- Quest captures from syngas with amines
- Air Products captures from syngas with VSA

Air Products SMR w/CCS

Source: Air Products and Chemicals, Inc., http://prphotolibrary.airproducts.com/

Negative Emissions Overview

- Bio-Energy with CCS (BECCS)
  - Same capture technology as in coal-fired power plants
  - We (MIT and Imperial College) have done some modeling and are encouraged by the results --paper just submitted to Environmental Research Letters
- Direct Air Capture (DAC)
  - Very expensive. I have been analyzing DAC for about 10 years and based on my analysis, I do not believe the lower cost numbers being floated today for DAC.
  - My beliefs are detailed here:
    - House *et al*., "Economic and Energetic Analysis of Capturing CO_2 from Ambient Air," *Proceedings of the National Academy of Sciences* 108, no.51 (December 2011). http://sequestration.mit.edu/pdf/1012253108full.pdf

BECCS

- Biomass removes CO_2 from the air - no absorbers or adsorbers needed
- Biomass provides the energy required for CCS and produces electricity as a by-product
- Biomass has issues revolving around land-use

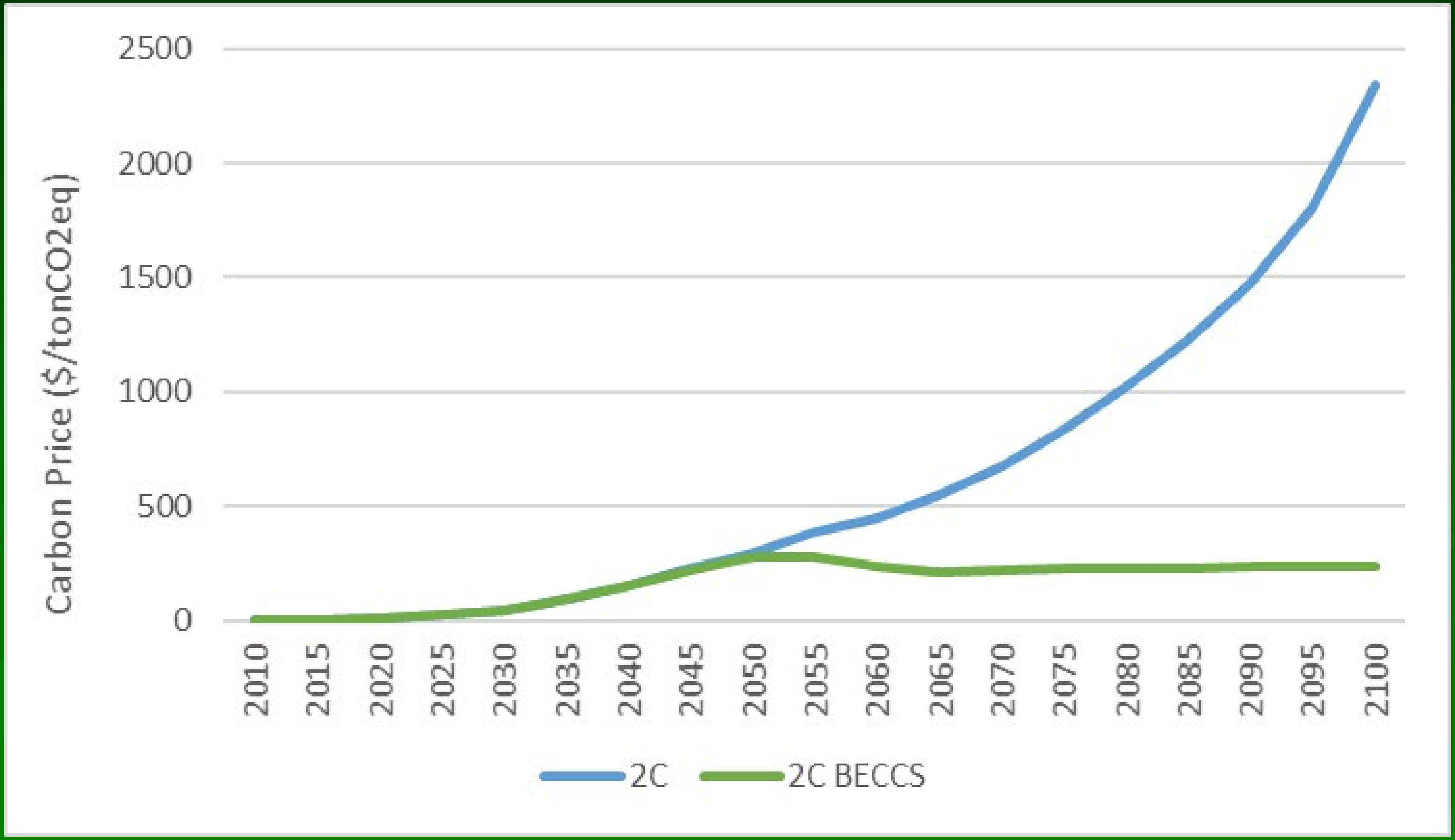
Status of BECCS

- Drax power station in England produces 2.6 GW of bioelecticity
- Boundary Dam (Canada) and Petra-Nova (Texas) capture over million tonnes per year CO_2 from power plants

Modeling of BECCS

- Land availability
- Biomass production and transport
- Biomass conversion to electricity
- CO_2 capture and storage
- Endogenous land use change
- Direct and indirect land use change emissions

Model Results – Carbon Price



Model Results – 2C Scenario

- Biomass used: 30 EJ in 2050, 320 EJ in 2100
- Negative emissions: 21 GtCO_2 in 2100
- Impact on food prices: ~5%

Land Use Change Impacts

- Ecosystem impacts and social acceptability were not modeled and could limit deployment
- Can be mitigated by regulations
- Forests can be maintained for multiple purposes

Direct Air Capture (DAC)

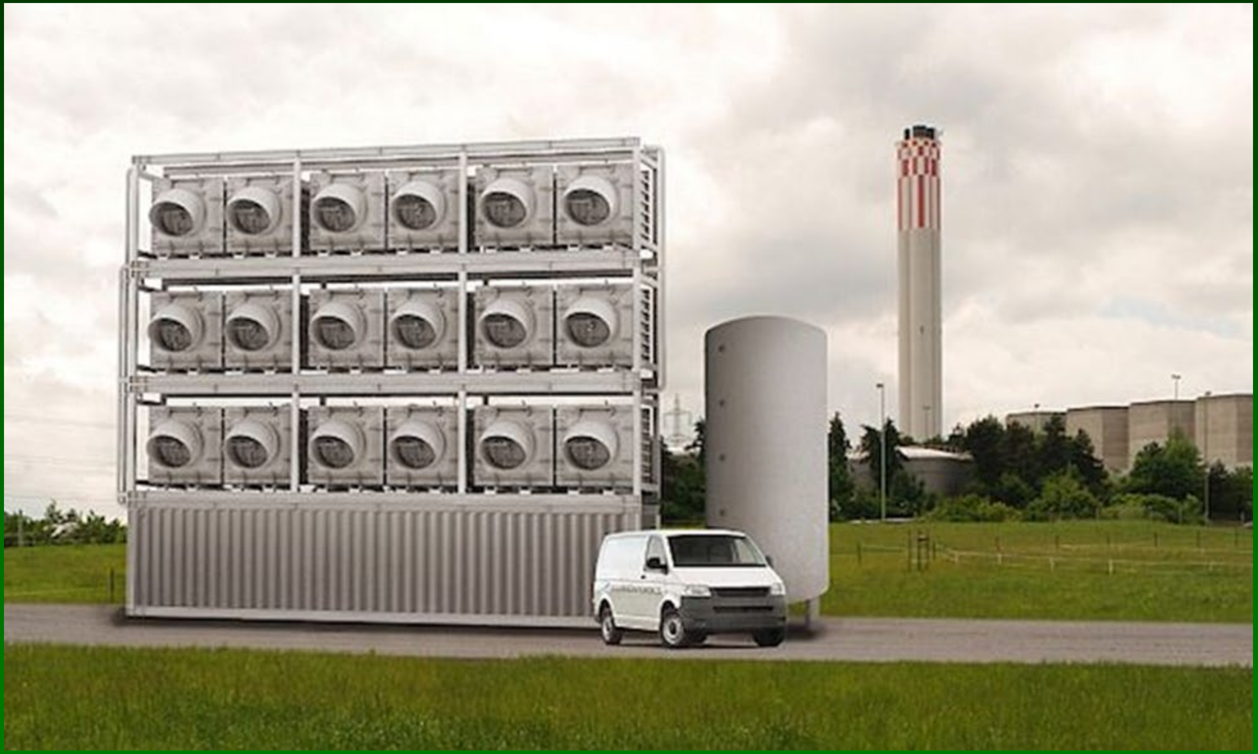
- DAC is a very seductive concept
- The question is not whether we can do it, but what is the cost
- My estimate is ~$1000 per ***net*** tonne of CO_2 removed
  - Requires significant energy
  - Must process large amounts of air

DAC

- Solid amine adsorbents (weak bases)
  - Climeworks
  - Global Thermostat
- Carbonates (strong bases)
  - Carbon Engineering

Petra Nova - W.A. Parish Plant CCS Absorber for 1.6 $MtCO_2$/yr

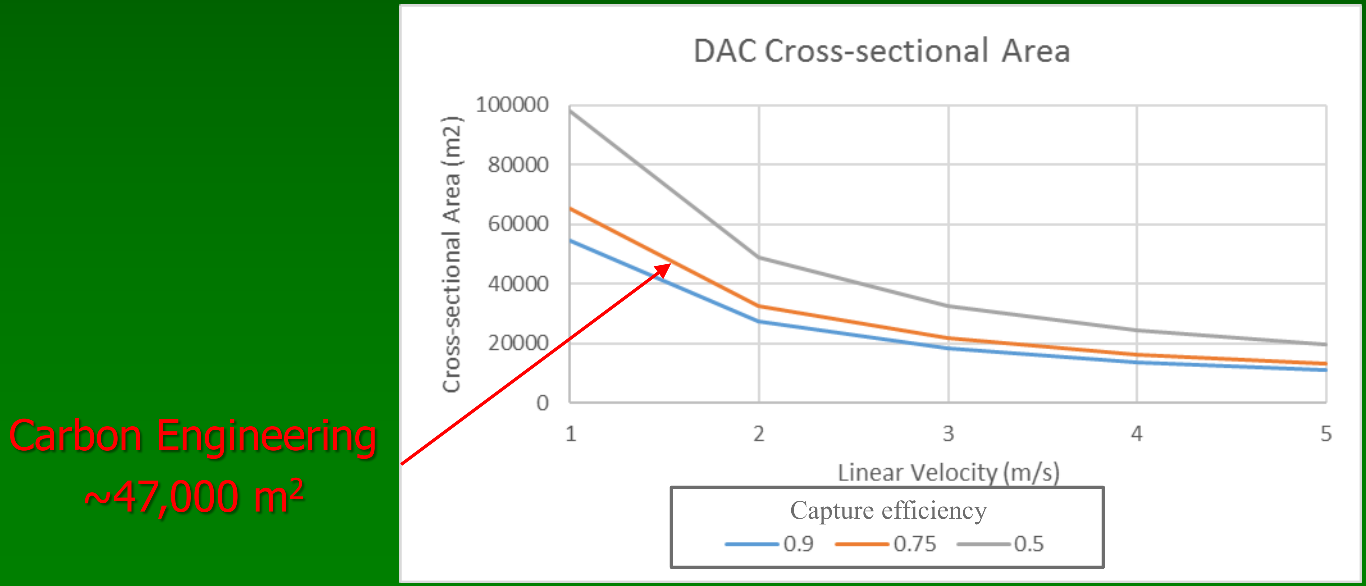
DAC



Climeworks DAC unit. Flow is horizontal, showing large cross-sectional area compared to the depth. Unit size is about 900 tCO_2/year.

Air Handling

- Air at 400 ppm CO_2 and 25°C
  - 0.72 g CO_2 per m^3 of air
  - 1.4 million m^3 of air contains 1 metric ton of CO_2
- Cross-sectional area required to capture 1 $MtCO_2$/year versus linear velocity and capture efficiency (assuming a 90% utilization efficiency):



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Negative Emission Summary

- Negative emissions technologies have significant implications for deep decarbonization scenarios
- DAC is expensive
- BECCS has great potential if a sustainable biomass supply can be developed

CCS Costs

- Beware of cost estimates: What do they really mean?
- Capture (gross) vs. avoided (net) costs
- <\$50/tCO_2 avoided – high purity or high pressure sources
- \$50-100/tCO_2 avoided – dilute sources (first mover costs higher)
- ~\$240/tCO_2 avoided – BECCS
- ~1000/tCO_2 avoided - DAC

Final Thoughts

- It is always cheaper to emit CO_2 to atmosphere than capture and store. So no matter how much we reduce capture costs, policy is still needed to create markets for carbon capture.
- Amines have issues, but they have been primary technology for carbon capture for past several decades; likely to remain so for at least one or two more decades.
- The potential applications for carbon capture are many and varied. Therefore, I envision a mix of multiple capture technologies will ultimately be in use.

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