Direct Air Capture

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Resources for the Future
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Difference Between Point-source vs Direct Air Capture

- Minimum work for separation may be derived from combined 1st and 2nd laws of thermodynamics
- Energy scales with dilution – > 3x more energy to do DAC vs exhaust streams
- 300x greater contactor area for CO₂ separation to do DAC vs exhaust
- High purity is desired for transport
- Direct air capture should not be seen as a replacement for avoiding carbon

Reference: Wilcox, Carbon Capture, 2012
Getting Started … how best to determine first projects

Low-carbon energy on converted lands

Power plants
- Coal
- Natural gas
- Geothermal
- Hydroelectric
- Nuclear

Low-carbon energy on converted lands

Wind potential

Industries for point source capture
- Cement
- Iron and steel
- Refining
- H₂ production
- Bioethanol

CO₂ capture [MtCO₂/yr]
- 0.1 – 0.5
- 0.5 - 1
- 1 - 5

Transportation
- CO₂ pipelines

Geologic reservoirs
- Sedimentary reservoirs
- Basalts
- Ultramafic rocks
- EOR

Retiring
- 2020 - 2030
- 2030 - 2050
- > 2050

Net Capacity [GW]

Ref: Hélène Pilorgé, U Penn (CEC Group)
Meeting Climate Goals Means Gigaton Removal by Mid-Century

Focus was on establishing a research agenda for negative emissions technologies

Major conclusion from the study:

“If the goals for climate and economic growth are to be achieved, negative emissions technologies will likely need to play a large role in mitigating climate change by removing globally 10 GtCO_2/yr by midcentury and 20 GtCO_2/yr by century’s end.”

http://nas-sites.org/dels/studies/cdr/
Negative Emissions Technologies

Coastal blue carbon

Accelerated chemical weathering of rocks

Direct air CO₂ capture

Biomass energy with carbon capture/storage

Afforestation/reforestation

Soil carbon

Biochar

Geologic formation

Basalt

http://nas-sites.org/dels/studies/cdr/
What Does Scrubbing CO$_2$ from a Point Source Look Like?

First patent filed by Bottoms in 1930!

"CO$_2$-free" gas out

Petra Nova – 1.4 Mt CO$_2$/year
115 Meters Tall Absorber
Today’s technologies are based on liquids or solid materials containing CO$_2$-grabbing chemicals.

Solvents rely on structured packing with solvent flow over the packing.

Solid sorbents rely on a honey-comb structure with chemicals (amines) bound to structure.
DAC – we understand it and are deploying it today

- Two leading technologies
  - Solvents - Carbon Engineering – economies of scale (plants ~ 1 MtCO$_2$/yr) and require high-quality heat (i.e., 900°C) – plant planned in PB in 2023
  - Solid Sorbents – Climeworks – modular and couples to low-quality (low-cost) heat (i.e., 100°C) – 15 plants globally (~ 2,000 tCO$_2$/yr)
- Energy breakdown is 80/20 in terms of thermal/electric
- Convert energy to power equates to ~ 300 MW/1 MtCO$_2$, but most of this is heat!
- There are lots of ways to make heat
- Increasing deployment will lead to efficiency increases. Today’s technologies are still far from the thermodynamic limit at roughly 5%
Where Might the Low-Carbon Energy Be Sourced?

**Natural gas power plants**
- Within 250 miles of the Permian basin pipelines
- Others

**Capacity [GW]**
- 0.5
- 1
- 5

**Retiring**
- 2020 - 2030
- 2030 - 2050
- > 2050

**Low-carbon opportunities on converted lands**
- Solar
  - PV only
  - PV or CSP
- Wind
- Potential

**Geologic reservoirs**
- Sedimentary reservoirs
- Basalts
- EOR [MtCO₂/yr]
  - < 0.5
  - 0.5 – 1.0
  - 1.0 – 5.0

**Net Capacity [GW]**

2020-2030: 194
2030-2050: 359
>2050: 126
DAC Siting Low-Carbon Available Thermal Energy
Results of a Recent Study from Our Team

- Regardless of the technology (solvent or sorbent), the energy distribution is 80% thermal and 20% electric for DAC
- Solid sorbent selected due to low-quality of thermal energy required (i.e., 100 °C)
- Thermal we’re considering from 3 pathways:
  - Geothermal – “waste” heat
  - Nuclear – 5% slipstream of steam
- Beneficial Reuse: EOR and beverage bottling industry
- Geologic Storage: USGS basin-level storage
- Ultimate Goal: delivered cost of compressed CO₂ at 99% purity
- Electricity prices and carbon intensity based upon grid mix of a given DAC site
- Careful of Definitions:
  - Cost of Capture – “break-even cost”
  - Cost of Net Delivered CO₂ – true cost from climate’s perspective

Reference: McQueen, Wilcox, et al., ES&T (2020)
DAC Siting and Costs – solid sorbents

Utilization & storage of CO₂
- EOR
- Geological sequestration
- Sequestration basins

Low-carbon energy sources
- Geothermal
- Nuclear

Transportation of CO₂
- CO₂ pipelines

Capture and injection rates [ktCO₂/yr]
- 1 - 50
- 50 - 100
- 100 - 500
- 500 - 1,000
- 1,000 - 10,000
- 10,000 - 100,000
- 100,000 - 1,000,000

Cost estimate ranges

Cost [$/tCO₂]
- Captured CO₂
- Net-delivered CO₂

Average cost

Geological sequestration
- 190
- 260
- 356

EOR
- 284
- 341
- 473

Reference: McQueen, Wilcox, et al., ES&T (2020)
Solid sorbent-based Direct Air Capture technology couples well to isolated and “low-quality” geothermal
Utilization as a Bridge to Permanent CO₂ Removal

US CO₂ market today is roughly 80 MtCO₂
• Largest use sector is EOR w/ price of $20-$40/tCO₂
• Smaller markets tend to command a higher CO₂ price $50-$400

Policy Incentives
• CA LCFS - $200/tCO₂
• Federal Tax Credit 45Q
  • $35/tCO₂ – utilization
  • $50/tCO₂ – dedicated storage

Emerging Markets
• Construction - gigatons
• Fuels – gigatons

Careful of permanent removal potential since goal is to avoid emissions AND CO₂ removal from air

References: Kuuskraa et al., NETL report, 2011; US EPA Database 2019; CARB 2018
A Hybrid Approach

Reference: NASEM, 2019
CO₂ emissions [MtCO₂/yr]

- < 0.1
- 0.1 – 0.5
- 0.5 – 1.0
- > 1.0

Industries
- Cement

Retiring
- 2020 – 2030
- 2030 – 2050
- > 2050
- unknown

Waste heat [MtCO₂/yr]

- < 1
- 1 – 2
- 2 – 5
- ≥ 5

Clinker replacement
- Cement kiln dust
- Pozzolan quarries
- Steel slag
- Coal fly ash

Others
- Lime

Technology change
- Oxygen (ASU)

Geologic reservoirs
- Sedimentary
- Basalts
- Ultramafic rocks
- EOR
- CO₂ pipelines

Ref: Hélène Pilorgé, U Penn (CEC Group)
Concrete = cement + water + aggregate

Combining:
- Point-source CO$_2$ capture
- Synthetic aggregate using DAC
- Fuel replacement with high-quality biomass waste and biodiesel
- Results in a maximum CO$_2$ removal of 116 kgCO$_2$/t concrete
- This can be compared against the carbon footprint of a more conventional approach today, which would emit 131 kgCO$_2$/t concrete.
Sourcing Alkalinity – Mine Waste as an Opportunity

Asbestos could be a powerful weapon against climate change (you read that right)

Scientists are exploring ways to use mineral waste from mines to pull huge amounts of carbon dioxide out of the air.

Photos taken by PhD student, Caleb Woodall
December 2019

Started New Open-Access Journal on Negative Emissions

Current Research Topics:
- Optimizing Data in Negative Emission Technologies Through Computation and Machine Learning
- Siting of Carbon Removal Strategies
- Scaling-Up Negative Emissions: The Power of Leveraging Policy, Philanthropy, Purchasing and Investment
- Beyond a Circular Economy: Building Negative Emission Systems in Transportation and Industry
- Global and national-level deep decarbonization studies have increasingly converged on the need for scaling-up Carbon Dioxide Removal (CDR) strategies, which are also referred to as negative emissions technologies (NETs). However, the scaling-up of these...
Reduce Carbon Sources

• Energy efficiency
• Low or zero-carbon fuel sources
• Conventional CCS

Enhance Carbon Sinks

Negative emissions technologies:

• Coastal blue carbon
• Terrestrial carbon removal and sequestration
• Bioenergy with carbon capture and sequestration (BECCS)
• Direct air capture
• Carbon mineralization
• Geologic sequestration

Reference: NASEM, 2019
Questions?

More Information:

https://www.ted.com/talks/jennifer_wilcox_a_new_way_to_remove_co2_from_the_atmosphere

https://www.npr.org/2019/06/07/730392105/jennifer-wilcox-how-can-we-remove-co2-from-the-atmosphere-will-we-do-it-in-time

http://nas-sites.org/dels/studies/cdr/

https://kleinmanenergy.upenn.edu/energy-policy-now/challenge-scaling-negative-emissions

https://kleinmanenergy.upenn.edu/policy-digests/essential-role-negative-emissions-getting-carbon-neutral

https://www.nae.edu/228941/The-Giving-Earth