CO₂ Capture: Near Term and Blue Sky Prospects

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In 15 minutes today, the world will:
- burn 0.96 million barrels of oil
- emit 1.5 million tons of CO₂

Future global energy demands will grow considerably and continue to be dominated by fossil fuels.

Fossil fuel use is changing the atmosphere, the oceans, and the global climate.
Climate Change – Personal Example

# of days with max. temp. < 10 C
(East Armidale, NSW)

Black line shows linear fit
(slope -5.7 days/decade)
Capture from Large Point Sources – Well Funded and Maturing

About 50% of man-made CO₂ emissions are from coal-fired power plants.

Huge R&D programs have invested in capturing CO₂ from these large point sources.

Reducing point source emissions to 10% of today’s level would still lead to atmospheric CO₂ > 450 ppm.

Tavoni et al., Environ. Model Assess. 16 (2011) 431
Membrane-based capture of CO$_2$ from flue gas appears feasible if units with ~1 million m$^2$ active surface area of high performance membranes can be developed.


Tampa Bay Water Desalination Plant
- 25 million gallons fresh water/day
- 9400 polyamide/polysulfone membranes
- ~400,000 m$^2$ membrane surface area
- 19 million gallons of salt solution/day diluted at nearby power plant
Core concept: MOF-polymer composite hollow fibers

Joint work by Sholl, Walton, Nair, Meredith, and Koros (GT)

Zeolite/Ultem composite membranes
(Koros, Jones, Nair et al., JACS 2009)
Hollow Fiber Spinning


Ultem®/ZIF-8 hollow fibers have been successfully spun and tested.
Hollow fiber membranes require many fewer modules than spiral wound membranes.

ZIF-8 Composite membranes with 100 nm skin layers would be economically competitive with best current spiral wound polymer membranes.

How much MOF is needed?
To apply to 3250 power plants world wide, 5,600 ton/year MOF required (assuming 3 year lifetime and using MOF only in skin layer).
More than 30% of man-made CO\textsubscript{2} emissions comes from small point sources (e.g. cars, planes)

11.2 GT worldwide from petroleum in 2010

No feasible technology exists to capture CO\textsubscript{2} from these sources at the point of emission

Worldwide transition away from liquid fuels for transportation is (at best) decades away

Capture from air and oceans can potentially offset emissions from disperse sources

If leakage rate from large-scale sequestration is 1% per year, net emission to the atmosphere over 50+ years is large

Capture from air or oceans could mitigate these “fugitive” emissions
Capturing CO\textsubscript{2} from dilute sources is possible, but is it a good idea??

We should grow trees/use solar energy/electrify our cars…. No single strategy can lead to managing net CO\textsubscript{2} emissions A comprehensive technological “toolbox” offers the broadest array of policy alternatives

CO\textsubscript{2} sequestration won’t work if reservoirs are not permanent

Dilute source capture can mitigate reservoir leakage, which is not possible with “standard” CCS from concentrated point sources

Capture from dilute sources will always be too expensive
This view put forward by Herzog et al. (Proc. Natl. Acad. 108 (2011) 20428)

Herzog et al.’s estimates based on simplified models and assume all energy input is electricity Detailed cost estimates are much lower (more on this later) Earlier critical APS report focused exclusively on NaOH process requiring high T calcination Policy decisions can only be made once technologies have been optimized and realistic costs can be established
Air Capture – An Emerging Area

Exhaust with CO₂ removed

Key:
- Yellow circle: Adsorbent
- Yellow circle: CO₂ for sequestration or conversion
- Green circle: Non-CO₂ gas
- Red circle: CO₂

Input gas

High T

Low T
Sorbents for Air Capture Are Available

Multiple highly selective solid sorbents for CO$_2$ have been developed:
- Hyperbranched aminosilicas (Jones)
- Amino-modified mesoporous silica (Sayari)

These show significant CO$_2$ uptake from ambient air.

- Choi, Jones et al., Environ. Sci. Technol. 45 (2011) 2420
- Wurzbacher et al., Energy Env. Sci. 4 (2011) 3584

Diamine-modified Mg/DOBDC

- Choi, Watanabe, Bae, Sholl, and Jones J. Phys. Chem. Lett. 3 (2012) 1136
Scalable Processes for Air Capture

Initial Cost Estimates for Cyclic Air Capture Processes


Estimates based on a 50 m³ shipping container-sized unit
Output: 700 t CO₂/yr at ~88% purity for each unit

Cost estimates for operation ($/t-CO₂-net)

<table>
<thead>
<tr>
<th>Electricity source</th>
<th>Scenario A (make steam)</th>
<th>Scenario B (waste steam)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>163</td>
<td>59</td>
</tr>
<tr>
<td>Natural gas</td>
<td>94</td>
<td>43</td>
</tr>
<tr>
<td>Hydro</td>
<td>88</td>
<td>44</td>
</tr>
</tbody>
</table>

NG is based on advanced combined cycle
Other renewables are more expensive than hydroelectricity
Costs include compression of CO₂ to 140 bar
Development Opportunities – Air Capture

CCS from large point sources has strong constraints on location of both capture and storage.

Capture from air or oceans can be performed at geographically disperse locations with scalable output.

What advantages can be realized from these characteristics?

How can CO₂ captured from dilute sources be effectively coupled with CO₂ utilization strategies?
- Algae for biofuels
- Agricultural greenhouses
Summary – Technology Development for CO₂ Capture

**Large point sources**
Critical cost barriers remain
Very high capital costs + uncertain regulations
limit near-term implementation

**CO₂ capture from air**
Technically feasible, questions remain about costs
Can only complement point source capture (not replace)
Interesting business opportunities exist around early implementation