Can carbon capture and storage forge the unusual alliances that finally bend the global emissions trajectory?

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## Four World Views

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<td>NO</td>
<td>A nuclear or renewables world unmotivated by climate.</td>
<td>Most people in the fuel industries and most of the public are here. 5°C.</td>
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<td>Environmentalists, nuclear advocates are often here. 2°C.</td>
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**Is climate change an urgent matter?**

- **NO**
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- **YES**
  - Environmentalists, nuclear advocates are often here. 2°C.
  - To encourage CCS one needs to be here. 3°C, tough job.
What happens when an irresistible force meets an immovable object?

*The irresistible force*: Fossil fuels, as vital as ever.

*The immovable object*: Climate change, which looms ominously.

Fossil fuels are so abundant that, for *any* cumulative-emissions target, even a weak one, *attractive* fossil fuel will be left in the ground.
Hydrocarbon resources in CO$_2$ units

1000 billion tons of CO$_2$ (1000 GtCO$_2$) result from burning:

- 2 trillion barrels of oil
- 20,000 trillion cubic feet of gas
- 300 billion tons of coal.

Resources in the ground, in units of GtCO$_2$:

<table>
<thead>
<tr>
<th>Resource</th>
<th>Amount (GtCO$_2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil</td>
<td>8,000</td>
</tr>
<tr>
<td>Gas excluding clathrates</td>
<td>3,000</td>
</tr>
<tr>
<td>Clathrates</td>
<td>40,000</td>
</tr>
<tr>
<td>Coal</td>
<td>20,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>70,000</strong></td>
</tr>
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Carbon-budget targets

The world’s fourth try at framing a global climate target:

1. Emission rate at some future date
2. Concentration never to be exceeded
3. Surface temperature never to be exceeded
4. Budgets (total emissions of CO$_2$ – past, present, future)

Notes:


CCS expands the budget.

Aerosols are assumed to have become unimportant.

Further assumptions: Land-use change. Methane and other GHGs.
1°C will result from anthropogenic CO₂ emissions to date.

2°C results from future emissions equaling historic emissions.

Four decades off at *current* rates of emissions and a hard stop, but a glide to zero requires immediate emissions reductions.

3°C will result from roughly a tripling the historical total.

Preventing 3°C is inconsistent with any further rise in emissions rates.
Analogous carbon emission trajectories

The probability is about 1/6 for both:

- getting >3°C while aiming for 2°C (being unlucky),
- getting <2°C while aiming for 3°C (being lucky).
Carbon budgets, resources, reserves, and “divestment”

Resources, not booked reserves, are the issue. Resources become reserves over decades (not years and not centuries).

As a result, carbon-budget considerations will principally affect the fossil fuel industry’s strategic investment decisions that create reserves from resources in new countries and in regions like the arctic.

Such investment decisions will get increased scrutiny.
“Solutions” can bring serious problems of their own.

Every “solution” has a dark side.

<table>
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<th>Conservation</th>
<th>Regimention</th>
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<td>Renewables</td>
<td>Competing uses of land; the “wild”</td>
</tr>
<tr>
<td>“Clean coal”</td>
<td>Mining: worker and land impacts</td>
</tr>
<tr>
<td>Nuclear power</td>
<td>Nuclear war</td>
</tr>
<tr>
<td>Geoengineering</td>
<td>Technological hegemony</td>
</tr>
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Two-sided optimization is required: taking into account both dangers from climate change and dangers from “solutions.”

Dangers from solutions are created by slamming on the brakes.

We must not privilege the atmosphere. Climate change is just one aspect of “fitting on the earth.”
“I will apply, for the benefit of the sick, all measures that are required, avoiding those twin traps of overtreatment and therapeutic nihilism.”

Hippocrates

$100/t\text{CO}_2$

There is wide endorsement of a carbon price, but reticence about how large it should grow to be. It is worth working out how various industries would respond to an economy-wide carbon price that is matched to the objective of inducing new investments.

For the sake of argument, consider $100/t\text{CO}_2$?

- *Upstream*, the impacts are particularly dramatic upstream. $100/t\text{CO}_2$ is:
  - $40$/barrel of oil
  - $5$/million Btu of natural gas
  - $200$/ton of high-quality coal.

- *Downstream*, if price-independent distribution costs are added, retail price increases are smaller, in percent. $100/t\text{CO}_2$ is:
  - $0.80$/U.S. gallon of gasoline
  - $0.08$/kWh electricity from coal
  - $0.04$/kWh electricity from natural gas.
“Emissions budgets” mean choices

The budget concept leads inexorably to choices:

- When?
- Whose?
- Used where?
- For what purpose?
- Which fossil fuels?

- Better options someday?
- Geopolitical stability
- “Fairness”
- Who judges?
- Those with the highest H/C ratio?

Which fossil fuels will we judge to be “unburnable” and leave in the ground?

Such decision-making is unprecedented.
The promise of CCS

The promise of CCS is that one can have one’s cake and eat it too. Carbon budgets for every target are expanded by CCS, including the targets for 2°C and 3°C.

CCS enables the fossil fuel industries to provide low-carbon fossil energy. New alliances are fostered.

CCS promotes a carbon price and creates new businesses.
Not having CCS is uniquely costly for $2^\circ$C

<table>
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<th>2100 concentrations (ppm CO$_2$eq)</th>
<th>no CCS</th>
<th>nuclear phase out</th>
<th>limited solar/wind</th>
<th>limited bioenergy</th>
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<tr>
<td>450</td>
<td>138%</td>
<td>7%</td>
<td>6%</td>
<td>64%</td>
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Symbol legend – fraction of models successful in producing scenarios (numbers indicate number of successful models)


“Good to have” is not the same as “available.”
The conceptual boundaries of CCS have expanded

CCS has become conceptually more complex with the inclusion of *uses* of CO$_2$.

There has been an expansion of the number of CO$_2$ sources and destinations under consideration.

I count seven distinct sources of CO$_2$. 
1. The “best” sources: natural CO$_2$ fields

- McElmo Dome, Colorado: 0.4 GtC in place
- 800 km pipeline from McElmo Dome to Permian Basin, west Texas, built in the 1980s

Two conclusions:

1. CO$_2$ in the right place is valuable.
2. CO$_2$ from McElmo was a better bet than CO$_2$ from any nearby site of fossil fuel burning.

Photo from David Hawkins
2. Pure CO$_2$ streams in industry

At In Salah, Algeria, natural gas purification by CO$_2$ removal plus CO$_2$ pressurization for nearby injection

Separation at amine contactor towers
3. CO$_2$ from power plants

NRG/PetraNova project, post-combustion CO$_2$ capture at a coal plant, pipeline to a depleted oil field for enhanced oil recovery. W.A. Parrish, Texas, USA. Groundbreaking: Sept. 5, 2014

Source: Julio Friedmann, private communication
4. The mining of previously sequestered CO₂

In the Sleipner project, offshore Norway, Statoil has pumped 1 MtCO₂/yr into the Utsira formation below the North Sea since 1996 – CO₂ that has been removed from natural gas produced from the Sleipner field, offshore Norway, in order to meet the standards of the European gas grid.

Retrievability has not been an objective (neither here nor in any other project to date).
5. CCS from distributed sources

Saudi Aramco has announced that it is developing a canister that would sit in the tailpipe of a vehicle and would remove CO$_2$ from the exhaust gas.

Can CO$_2$ be collected like aluminum cans?
6. Carbon scrubbed from biomass

Bioenergy with CCS (BECCS) scrubs the atmosphere of CO₂ by first removing carbon from the atmosphere by photosynthesis and then capturing and storing the carbon somewhere else.

BECCS makes immense demands on land (see below), as do the three other biocarbon strategies for mitigation:

- afforestation
- biofuels
- conventional biopower
7. CO$_2$ captured directly from the atmosphere
Destinations

There are also seven distinct destinations.

The objective is storage:

1. In solids (porous solids, cavities)
2. In fluids (the ocean)

The objective is use:

3. Using its physical properties (EOR, supercritical working fluid, ice, fizz)
4. Chemical transformation to fuels*
5. Chemical transformation to high-value organics*
6. Biofuel feedstock (as in real greenhouses)
7. Air (to warm the planet deliberately)

* with energy inputs
Sources and destinations

With seven distinct sources and seven distinct destinations, there are 49 matrix elements. Nearly all are worth considering.

**Sources**
1. Nature’s “gift”
2. Pure stream
3. Power plant
4. Stored earlier
5. Distributed
6. Biocarbon
7. Air

**Destinations**
1. Deep aquifers
2. Ocean
3. EOR
4. Fuels
5. Costly organics
6. Biofuels
7. Air
Today, commercial

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Small-scale field studies under way

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*Observation:* Many combinations have hardly been explored.
Enhanced oil recovery (EOR)

EOR is lower-carbon oil, because the default is oil production without CO\textsubscript{2} storage.

EOR is sometimes called “associated storage.” Other forms of associated storage include CO\textsubscript{2} injection to maintain pressure. CO\textsubscript{2} has competitors as an EOR fluid, including methane. Best fluid depends on the reservoir.

Today, the EOR industry is wary of adding a CO\textsubscript{2} storage objective. Understandably, it sees only hassle.

Someday, storing CO\textsubscript{2} and producing oil may yield comparable revenue. EOR will then be done very differently. Typical today: 3 bbl/tCO\textsubscript{2}, and higher is good. Someday, lower may be good.
The off-ramp to synfuels from CCS

Carbon Recycle: Carbon in fossil fuel is burned to make CO$_2$, is captured, becomes a fuel (with external energy), and is burned again.

Probably, it is not captured a second time.

*Side calculation:* At what cost of CO$_2$ does it contribute as much to the cost of synfuels as $1$/kgH$_2$?

Use $3$ H$_2$ + CO$_2$ $\rightarrow$ CH$_2$+ 2 H$_2$O  (CH$_2$ $\approx$ gasoline, diesel)

Answer: $140$/tCO$_2$.

H$_2$ at $1$/kgH$_2$ is matched to 3¢/kWh power, 100% efficient electrolysis

Note: $1$/kgH$_2$ $\approx$ $1$/gal gasoline-eq,
The Future Coal or Natural Gas Power Plant

Shown here: After 10 years of operation of a 1000 MW coal plant, 60 Mt (90 Mm$^3$) of CO$_2$ have been injected, filling a horizontal area of 40 km$^2$ in each of two formations.

Assumptions:
- 10% porosity
- 1/3 of pore space accessed
- 60 m total vertical height for the two formations.

• Note: Plant is still young.

Injection rate is 150,000 bbl(CO$_2$)/day, or 300 million standard cubic feet/day (scfd). That’s 3 billion barrels, or 6 trillion standard cubic feet, over 60 years.
Minimal leakage up old wells

“The best data we have on the state of old wells indicate that leakage of CO\textsubscript{2} should not be excessive and that CO\textsubscript{2} injection should be able to proceed without leakage along old wells being a show stopper.”

Michael Celia, Princeton University

Source of figure above: Michael Celia

Unreacted H-type cement

Cement after 3 weeks in flow-through reactor at 50\textdegree{}C and pH 2.4. Color variation is due to changes in oxidation in iron impurities.
Pore space is unlikely to be a problem.

Pore space is a geological resource, like tin. It gets larger with effort, with invention, and with price.

There is unlikely to be any salient limit on geological pore space.
The end game

Capture

Transport

Storage

Pre-investment

Post-closure

Source: Zero Emissions Platform (ZEP), from Gardiner Hill
In the Sahara, getting to know abandonment

At In Salah, Algeria, natural gas purification by CO₂ removal plus CO₂ pressurization for nearby injection

Separation at a mine contactor towers
Carbon Dioxide Removal (CDR): Many versions

Direct air capture (DAC) with chemicals

Biological strategies (Bio-CDR)
  Biopower with CCS (BECCS)
  Afforestation
  Ocean fertilization

Chemical strategies
  Ocean alkalinity
  Enhanced weathering
Carbon Dioxide Removal (CDR) from air

CDR can counter recalcitrant decentralized CO$_2$ emissions, such as emissions from buildings and vehicles, that prove expensive to reduce by other means.

CDR might someday enable the world to lower the atmospheric CO$_2$ concentration gradually.

Factor of 2 from negative feedbacks: Oceans will outgas, biosphere will shrink

Formidable challenge of “net carbon.”
“Net-carbon” raises CDR cost $/(tCO_2 \text{ no longer in the atmosphere})

The cost-multiplier, \( y \), is the ratio of avoided cost to capture cost:

\[ y = \frac{1}{1 - x}, \]

where \( x \) is the amount of CO_2 emitted per CO_2 captured.

Example: The APS benchmark system has \( x = 0.3 \). Grid power runs the fans and compressor, but regeneration heat is provided by natural gas with CCS. Without CCS, \( x = 0.7 \).
CDR: not matched to emergencies

Lower the CO₂ concentration by **100 ppm** (capture **1500 GtCO₂**):

A. Over 100 years (e.g., 2050-2150)
B. Over 10 years (e.g., 2050-2060)

"Pace" (slope, rate of increase in removal capability):

(A) 0.30 GtCO₂/yr²; (B) 30 GtCO₂/yr² (100 times larger).

The pace in (B) is far too fast for CDR. It is equivalent to canceling the entire global fossil-fuel system in one year.
First things first

It will almost surely be much cheaper to capture CO$_2$ from the flue gas of a coal power plant than from ambient air, where it is 300 times more dilute. At a natural gas plant, 100 times.

Accordingly, aggressive deployment of DAC makes little sense until the world has largely eliminated *centralized and concentrated* sources of CO$_2$ emissions, especially at coal and natural gas power plants:

- by efficiency gains that make the plants unnecessary
- by substitution of non-fossil alternatives
- by capture of nearly all of the plants’ CO$_2$ emissions.
The capture research frontier: materials and systems

Priority areas include:

Strategies for contacting gases and chemicals
New chemistries for sorption and regeneration
Membranes
Electrolytic separation (e.g., carbonate fuel cell)
Materials that can operate effectively and efficiently over tens of thousands of consecutive cycles
The storage research frontier: Integrated management of the deep-below-ground

The deep-below-ground cries out for the coordination of the extraction of hydrocarbons, the mining of geothermal heat, and the isolation of CO\textsubscript{2} and other wastes – while taking advantage of that isolation to do neutrino science.

What goal for CO\textsubscript{2} storage integrity is good enough? As in so many other domains, the great is the enemy of the good.

It is essential, and difficult, to earn the public’s trust.
U.S. CO$_2$ pipelines: another infrastructure

U.S.: 60 MtCO$_2$/yr, 0.25 Mbbl/day.
Average: 1.5 bbl/tCO$_2$. Range 1-3 bbl/tCO$_2$. 
Don’t kid ourselves: A huge infrastructure

Density ratios: Coal $\approx 2$; Oil $\approx 1$ to $1.5$; natural gas (at 1000 m) $\approx 0.1$.

One wedge $\approx 4$ Gt(supercritical $\text{CO}_2$)/yr. Volume $\approx 20$ billion bbl/yr, about half the volumetric flow rate of the world’s oil.
Hype is cruel

The various publics concerned about climate change want CDR to be available, inexpensive, and risk-free.

It is obligatory, therefore, for experts not to create false hopes – in this case, not to allow our audiences to infer that humanity can “solve” climate change while being relaxed about fossil fuels.
Grounds for optimism

1. The signals from climate change are just beginning to emerge.

2. The world today has a terribly inefficient energy system.

3. Most of the 2065 physical plant is not yet built.

4. Carbon emissions have just begun to be priced.

5. Alliances across countries and national subcultures are just beginning to be made.

6. Very smart scientists and engineers now find energy problems exciting.