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

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Four World Views

		Are fossil fuels hard to displace?	
		NO	YES
Is climate change an urgent matter?	NO		
	YES		

Four World Views

		Are fossil fuels hard to displace?	
		NO	YES
Is climate change an urgent matter?	NO	A nuclear or renewables world unmotivated by climate.	Most people in the fuel industries and most of the public are here. **5ºC.**
	YES	Environmentalists, nuclear advocates are often here. **2ºC.**	To encourage CCS one needs to be here. **3ºC, 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 $GtCO_2$:

Oil	8,000
Gas excluding clathrates	3,000
Clathrates	40,000
Coal	20,000
Total	**70,000**

Source: Rogner, H-H, 1997. "An assessment of world hydrocarbon resources," *Ann. Rev. Energy and Env*. *22*, pp. 217-262. The table reworked here is on p. 249. Estimates include "additional" resources.

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:

Given legitimacy in *IPCC AR5, Working Group I*, 2013.

CCS expands the budget.

Aerosols are assumed to have become unimportant.

Further assumptions: Land-use change. Methane and other GHGs.

Cumulative emissions and temperature

1°C will result from anthropogenic CO_2 emissions to date.

2°C results from future emissions equaling historic emissions.

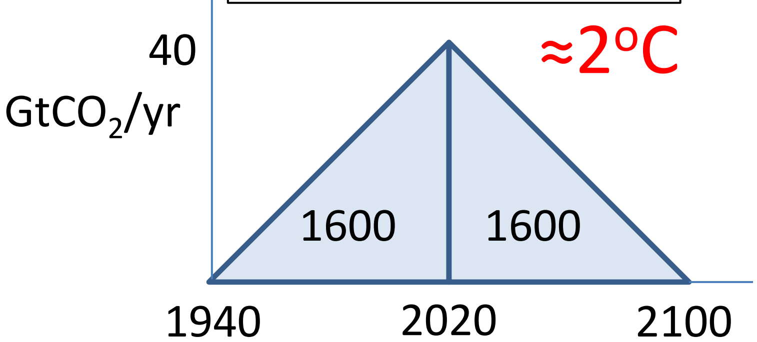
Four decades off at *current* rates of emissions and a hard stop,
but a glide to zero requires immediate emissions reductions.

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

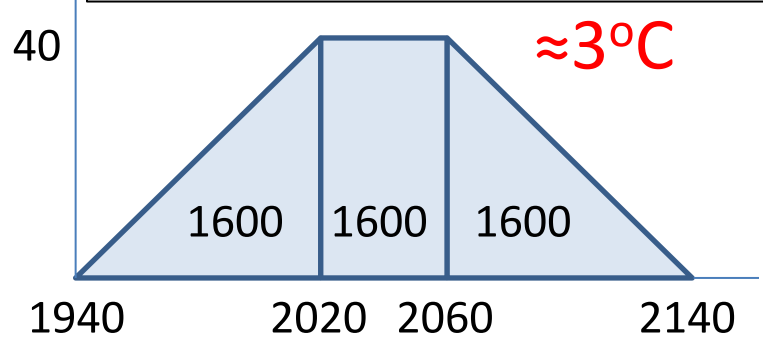
Preventing 3°C is inconsistent with any further rise in emissions rates.

Analogous carbon emission trajectories

"Hubbert peak" equivalent



Add one rectangle:
40 billion tCO_2/yr* 40 yrs



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.

Conservation	Regimentation
Renewables	Competing uses of land; the "wild"
"Clean coal"	Mining: worker and land impacts
Nuclear power	Nuclear war
Geoengineering	Technological hegemony

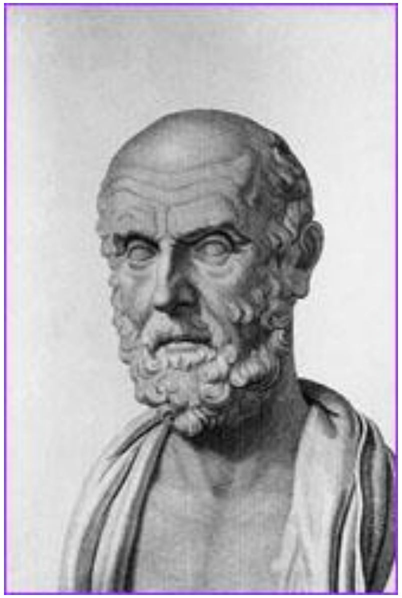
Two-sided optimization is required: taking into account both dangers from climate change and dangers from "solutions."
Dangers from solutions are created by slamming on the brakes.

We must not privilege the atmosphere. Climate change is just one aspect of "fitting on the earth."

Patient 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



*** Modern version of the Hippocratic oath, Louis Lasagna, 1964, http://www.pbs.org/wgbh/nova/doctors/oath_modern.html**

$\$100/tCO_2$

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 **$\$100/tCO_2$**?

- *Upstream*, the impacts are particularly dramatic upstream. **$\$100/tCO_2$** 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. **$\$100/tCO_2$** 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.

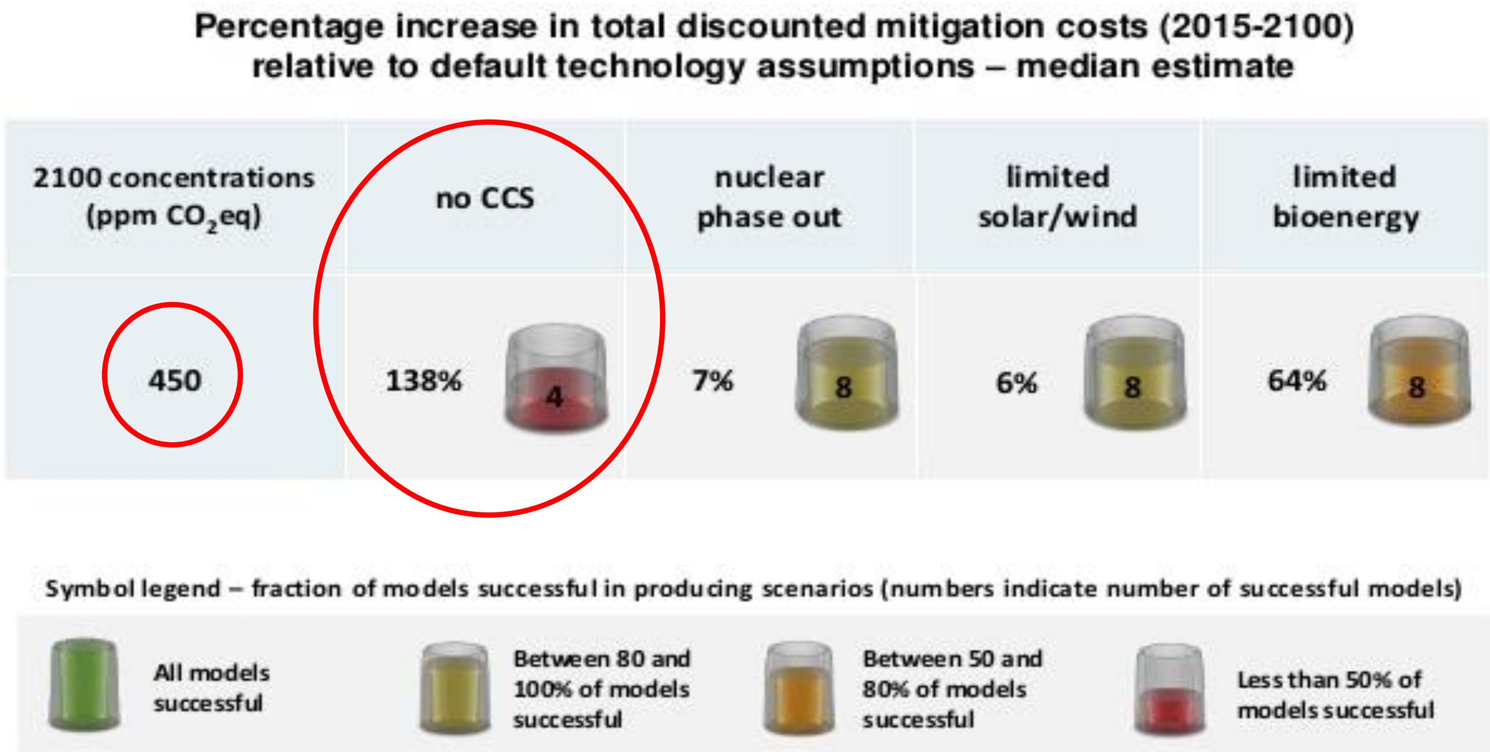
The promise of CCS

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^oC and 3^oC.

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°C



Source: *IPCC Fifth Assessment Synthesis Report, November 2014.*

"Good to have" is not the same as "available."

The conceptual boundaries of CCS have expanded

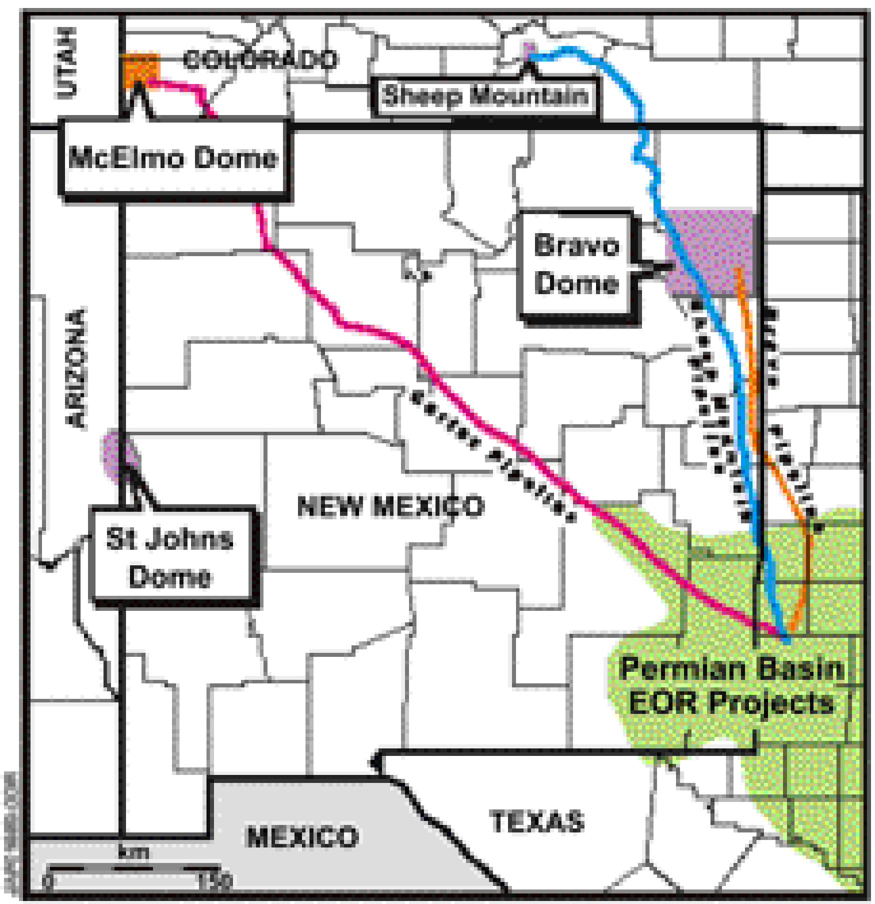
CCS has become conceptually more complex with the inclusion of *uses* of CO_2.

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.

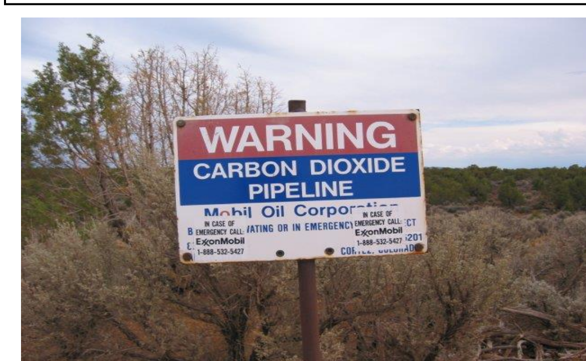
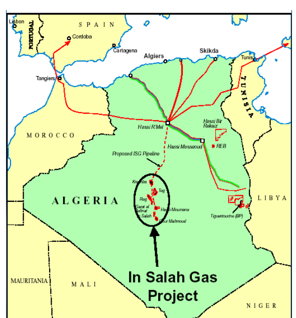


Photo from David Hawkins

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



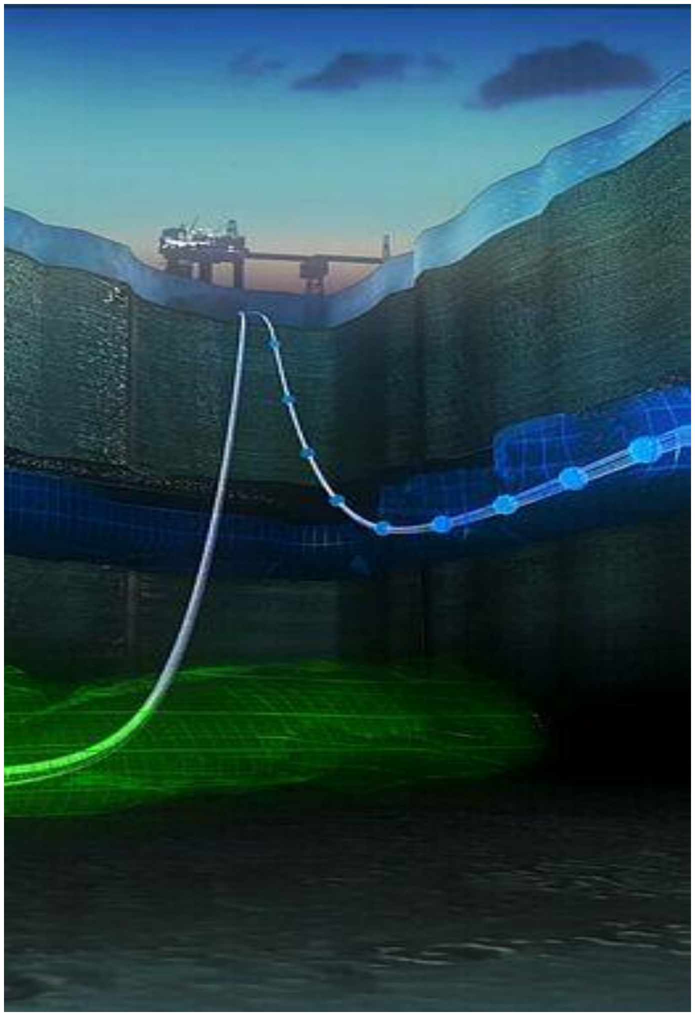
Separation at amine contactor towers

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 CO_2



Graphic courtesy of Statoil ASA

In the Sleipner project, offshore Norway, Statoil has pumped 1 $MtCO_2$/yr into the Utsira formation below the North Sea since 1996 – CO_2 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?

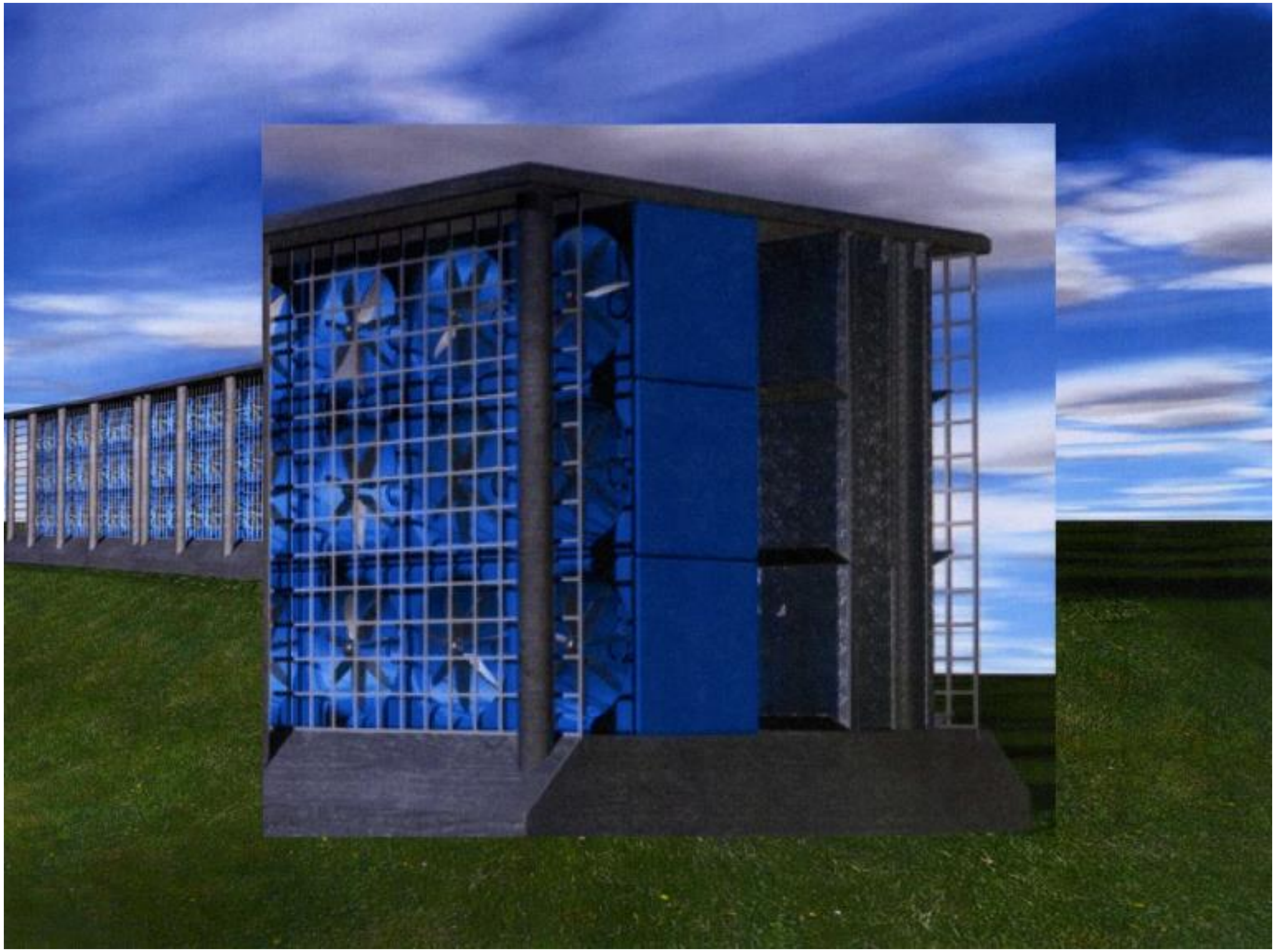
6. Carbon scrubbed from biomass

Bioenergy with CCS (BECCS) scrubs the atmosphere of CO_2 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



Source: David Keith, MIT talk, Sept. 16, 2008

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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Today, demos

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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_2 storage

EOR is sometimes called "associated storage." Other forms of associated storage include CO_2 injection to maintain pressure. CO_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_2 storage objective. Understandably, it sees only hassle.

Someday, storing CO_2 and producing oil may yield comparable revenue. EOR will then be done very differently. Typical today: 3 bbl/tCO_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?

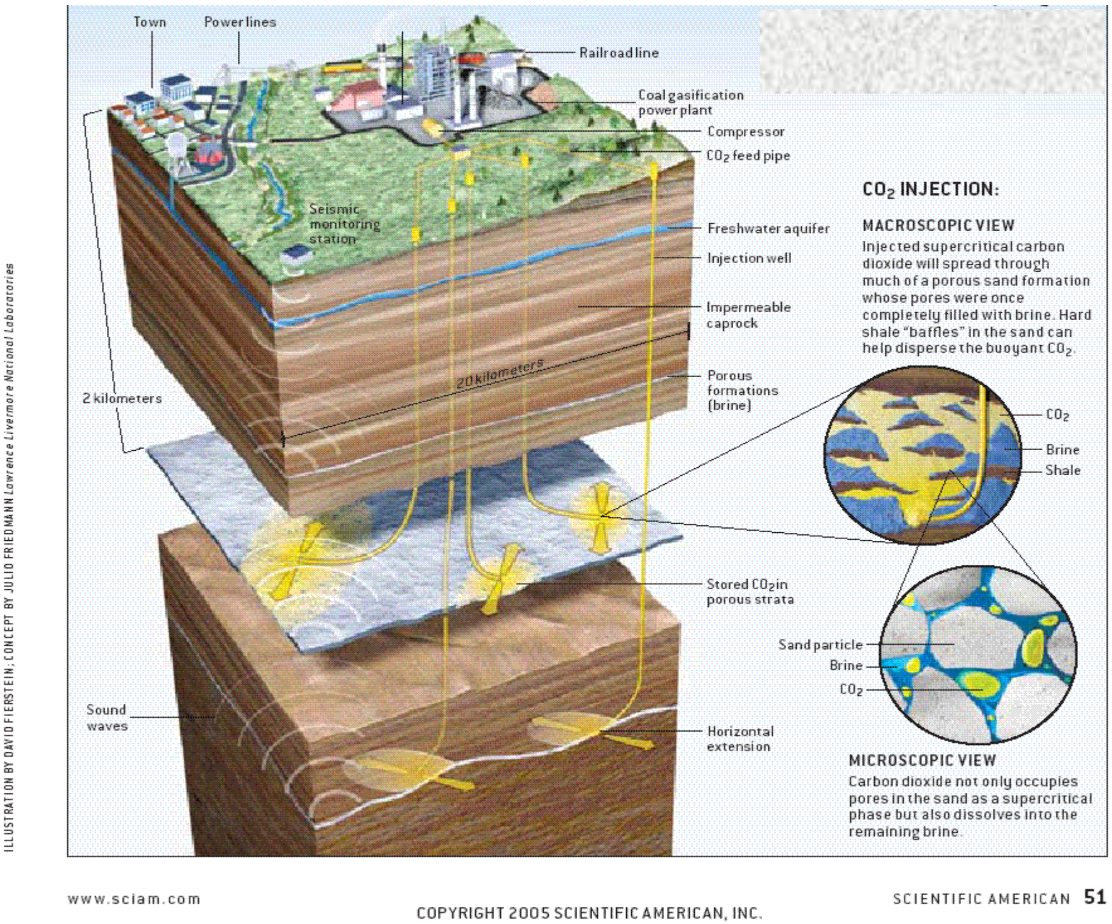
Use $3\ H_2 + CO_2 \rightarrow CH_2 + 2\ H_2O$ ($CH_2 \approx$ gasoline, diesel)

Answer: **\$140/t$\mathbf{CO_2}$**.

H_2 at \$1/kgH_2 is matched to 3¢/kWh power, 100% efficient electrolysis

Note: \$1/kgH_2 ≈ \$1/gal gasoline-eq,

The Future Coal or Natural Gas Power Plant



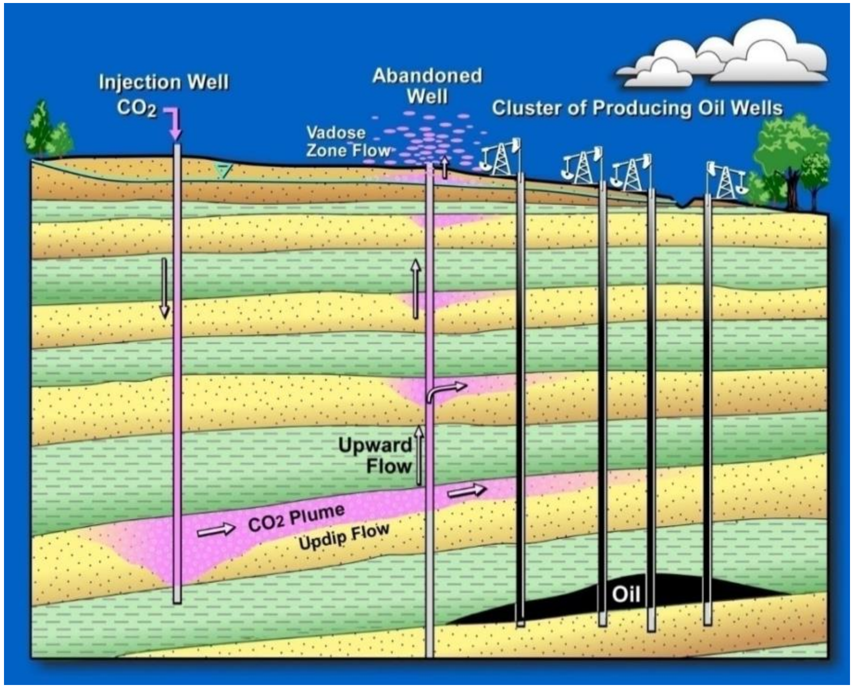
Shown here: After 10 years of operation of a 1000 MW coal plant, 60 Mt (90 Mm^3) of CO_2 have been injected, filling a horizontal area of 40 km^2 in each of two formations.

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.

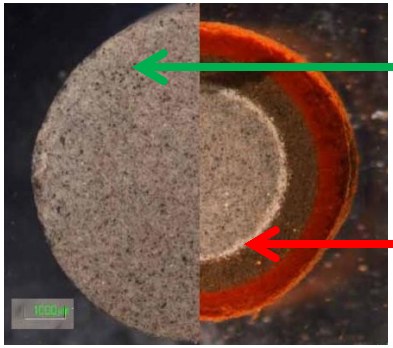
Minimal leakage up old wells



Source of figure above: Michael Celia

"The best data we have on the state of old wells indicate that leakage of CO_2 should not be excessive and that CO_2 injection should be able to proceed without leakage along old wells being a show stopper."

Michael Celia, Princeton University



Unreacted H-type cement

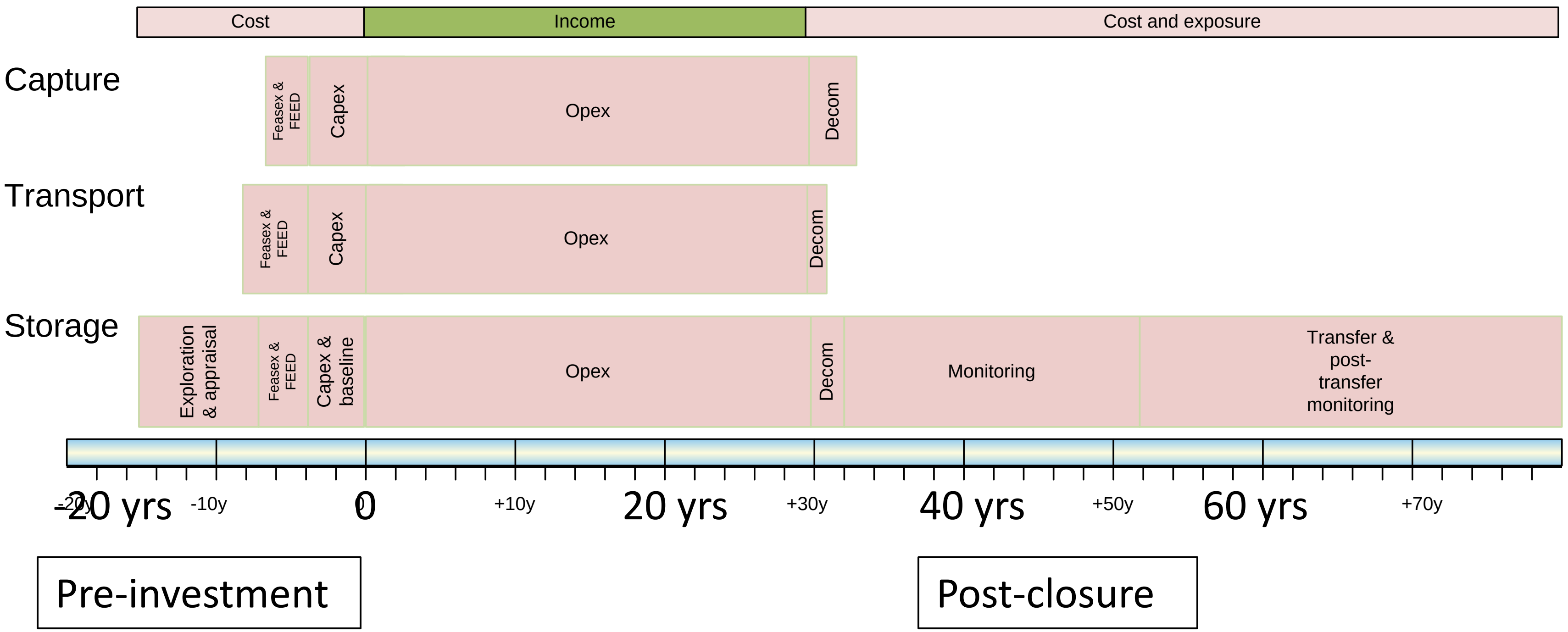
Cement after 3 weeks in flow-through reactor at 50^{o}C and pH 2.4. Color variation is due to changes in oxidation in iron impurities.

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.

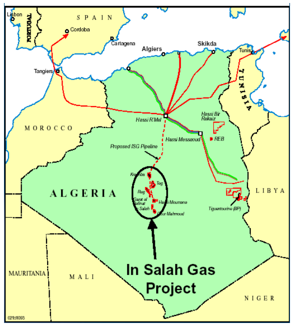
The end game



Source: Zero Emissions Platform (ZEP), from Gardiner Hill

In the Sahara, getting to know abandonment

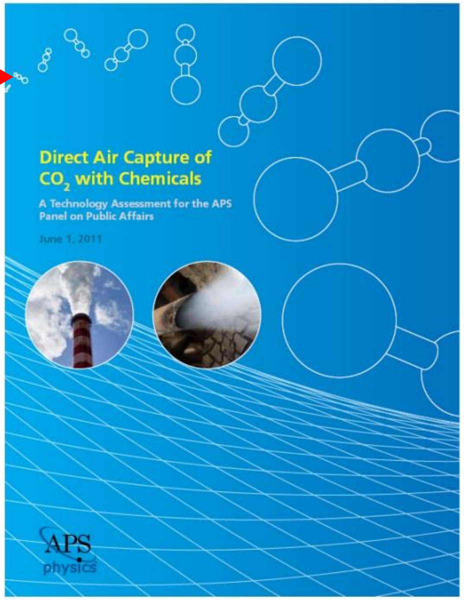
At In Salah, Algeria, natural gas purification by CO_2 removal plus CO_2 pressurization for nearby injection



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

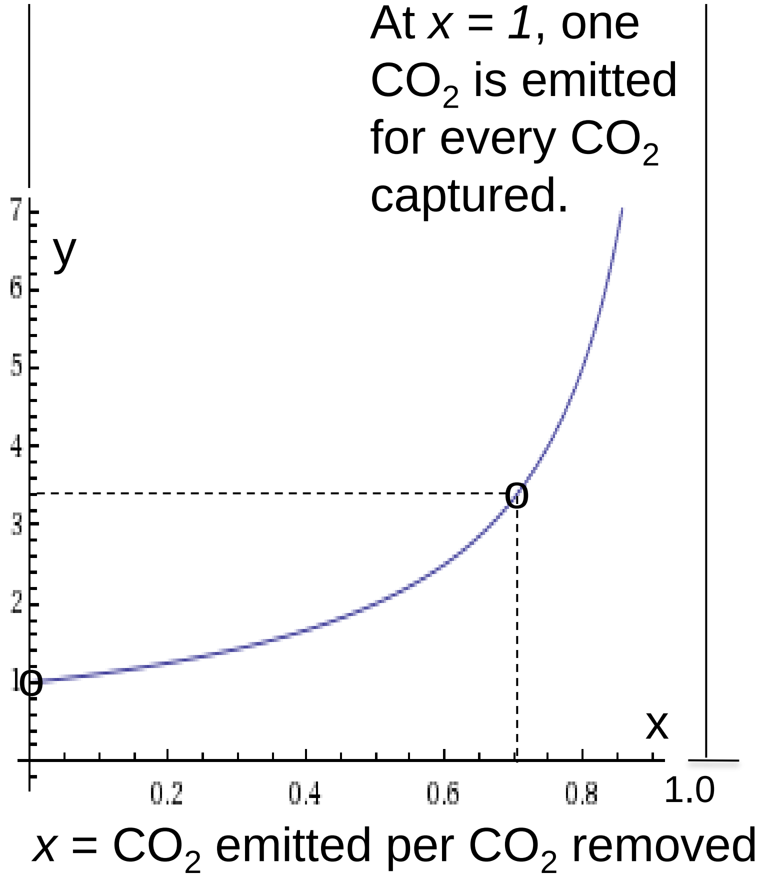
Formidable challenge of “net carbon.”

"Net-carbon" raises CDR cost $/(tCO_2$ no longer in the atmosphere)

The cost-multiplier, *y*, is the ratio of avoided cost to capture cost:

$$y = 1/(1 - x),$$

where *x* is the amount of CO_2 emitted per CO_2 captured.

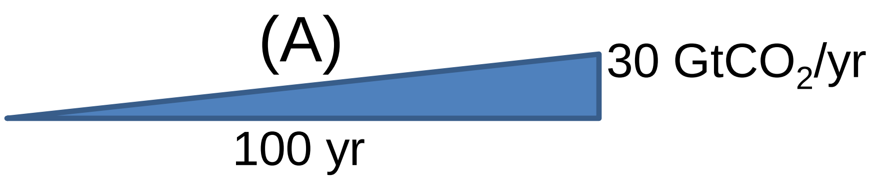


Example: The APS benchmark system has $x = 0.3$. Grid power runs the fans and compressor, but regeneration heat is provided by natural gas with CCS. Without CCS, $x = 0.7$.

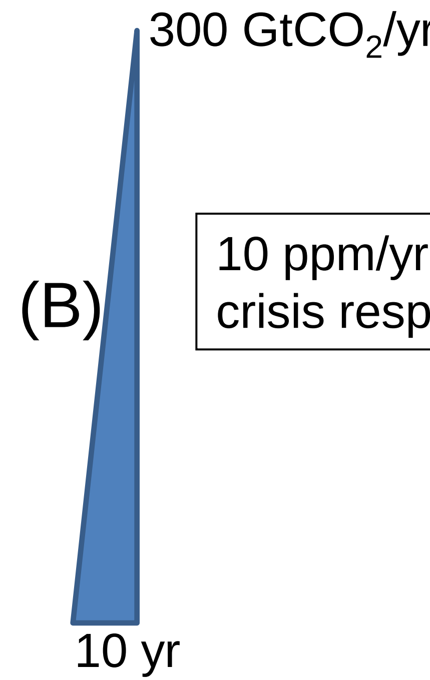
CDR: not matched to emergencies

Lower the CO_2 concentration by **100 ppm** (capture **1500 $GtCO_2$**):

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



1 ppm/yr: plausible build-rate?



10 ppm/yr:
crisis response

"Pace" (slope, rate of increase in removal capability):
(A) 0.30 $GtCO_2/yr^2$; (B) 30 $GtCO_2/yr^2$ (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

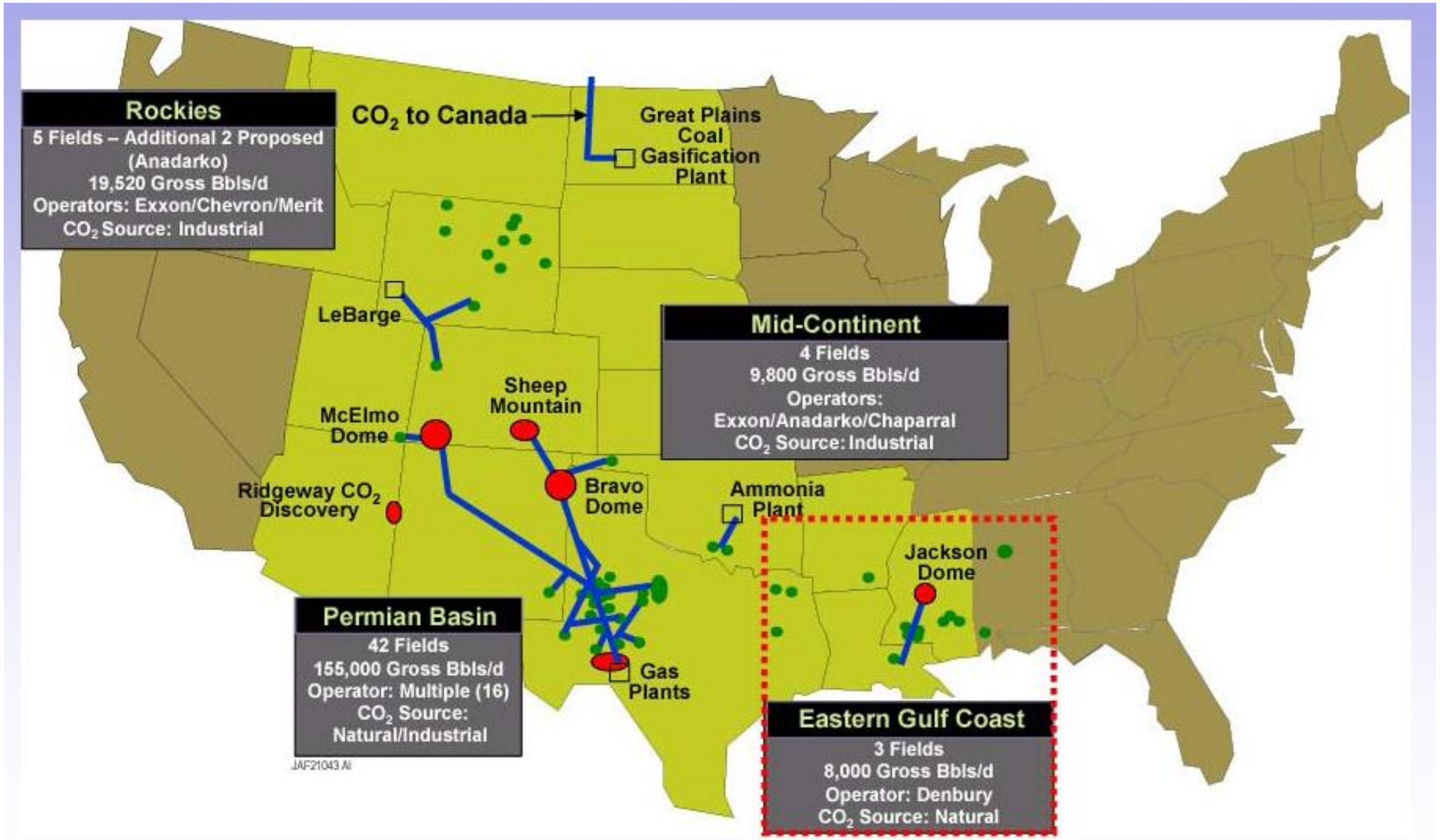
The storage research frontier: Integrated management of the deep-below-ground

The deep-below-ground cries out for the coordination of the extraction of hydrocarbons, the mining of geothermal heat, and the isolation of CO_2 and other wastes – while taking advantage of that isolation to do neutrino science.

What goal for CO_2 storage integrity is good enough? As in so many other domains, *the great is the enemy of the good*.

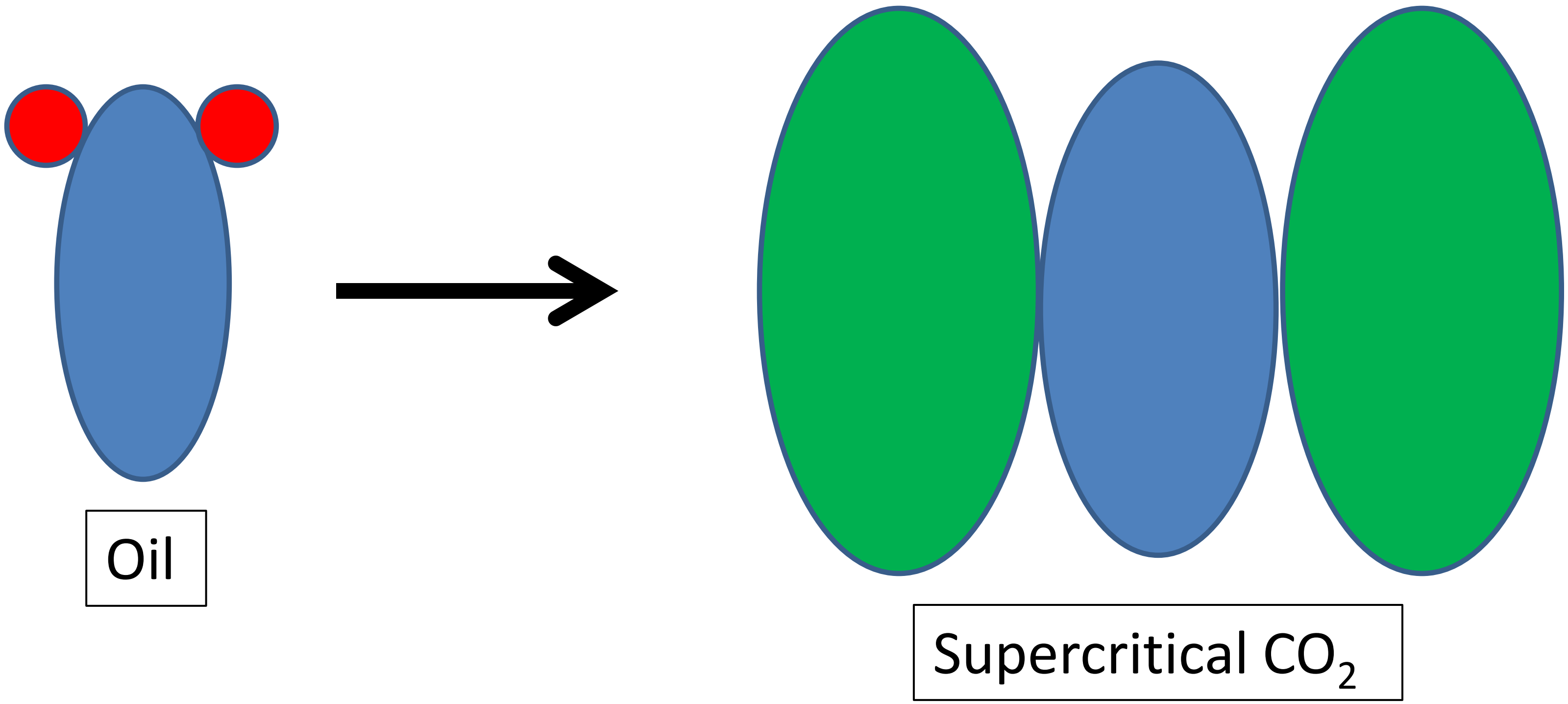
It is essential, and difficult, to earn the public's trust.

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 ≈ 2; Oil ≈ 1 to 1.5; natural gas (at 1000 m) ≈ 0.1.

One wedge ≈ 4 Gt(supercritical CO_2)/yr. Volume ≈ 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.