Global Carbon Management
and the Role of Hydrogen

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Outline of talk

1. The global carbon as a problem of benefits and costs of avoiding carbon build-up to various levels and at various rates.

2. How hydrogen fits within the problem of global carbon.


4. Achieving stabilization “slice by slice.”

Under each topic, give unsolicited advice to GCEP.
What if the fossil fuel future is robust, but the Greenhouse problem is severe?

<table>
<thead>
<tr>
<th>Will the Fossil Fuel System Wither Away?</th>
<th>Will the Greenhouse Problem Wither Away?</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>YES</strong></td>
<td>A nuclear or renewables world unmotivated by climate.</td>
</tr>
<tr>
<td><strong>NO</strong></td>
<td>Assumed by most people in the fuel industries and most of the public</td>
</tr>
<tr>
<td><strong>YES</strong></td>
<td>Assumed by most environmentalists</td>
</tr>
<tr>
<td><strong>NO</strong></td>
<td>OUR WORKING ASSUMPTIONS</td>
</tr>
</tbody>
</table>
CO₂ emissions per capita from 10 largest emitting countries and world

# Global Fossil Carbon Resources, Gt(C)

<table>
<thead>
<tr>
<th>Resource</th>
<th>Base</th>
<th>Additional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional oil (85 wt. % C)</td>
<td>250</td>
<td>1550</td>
</tr>
<tr>
<td>Unconventional oil</td>
<td>440</td>
<td></td>
</tr>
<tr>
<td>Conventional nat. gas (75% C)</td>
<td>240</td>
<td>220</td>
</tr>
<tr>
<td>Unconventional nat. gas</td>
<td>250</td>
<td>10600</td>
</tr>
<tr>
<td>Clathrates</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal (70% C)</td>
<td>3400</td>
<td>2900</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>4600</td>
<td>15300</td>
</tr>
</tbody>
</table>

Source Rogner, *Ann. Rev. Energy and Env.* 22, p. 249. Also used: 1 toe = 41.9 GJ; 20.3 kg(C)/GJ(oil); 13.5 kg(C)/GJ (gas); 24.1 kg(C)/GJ(coal).
What if 5600 Gt carbon were removed from below ground?
The Rosetta Stone

$1 \text{ ppm(v)} = 2.1 \text{ Gt(C)}$

This connects the worlds of energy and environmental science

Example: We are currently extracting from below ground and adding to the atmosphere about 6 billion metric tons of carbon per year. In our atmosphere, currently, about 370 of every million molecules are $\text{CO}_2$. A year from now, therefore, about 373 of every million molecules will be $\text{CO}_2$, if there are no removal mechanisms (“sinks”).

There are sinks, both land and ocean sinks. Today they remove $\text{CO}_2$ from the atmosphere at about half the rate that we are adding $\text{CO}_2$. 

The Rosetta Stone
2100 Mt(C) = 1 ppmv(CO₂)

http://www.eia.doe.gov/emeu/international/total.html#IntlCarbon
Atmospheric CO$_2$ Concentration with and without 1980-99 sinks
400,000 Years of CO₂ Data: Four Ice Ages

Variations of atmospheric CO₂ over glacial/interglacial times (Petit et al. 1999, Keeling and Whorf 1999). Circle at upper right shows current concentration.
Impact of Increased $\text{CO}_2$ on Ocean Circulation

North Atlantic Thermohaline Circulation Intensity, GFDL R15 climate model

$10^6 \text{m}^3/\text{sec}$

Year

Control

$2x\text{CO}_2$

$4x\text{CO}_2$
A loose consensus: Avoid doubling the pre-industrial concentration

*Pre-industrial CO$_2$ concentration in atmosphere:* 280 ppm  
*Today’s value:* 370 ppm  
*Doubled value:* 560 ppm

Doubling is the most widely used boundary between acceptable and unacceptable greenhouse-related environmental disruption. Doubling will occur after *roughly* the extraction of 1000 billion tonnes of fossil carbon. We are already one-third of the way there. We are heading for a doubling within *roughly* 50-75 years.

Is “doubling” the appropriate reference ratio? Here is where the important scientific uncertainties and human judgments are found.
Unsolicited advice #1

Incorporate environmental science into your research program.

Otherwise, you will not internalize answers to the key question: Why work so hard at this?
Outline of talk

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2. How hydrogen fits within the problem of global carbon.


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Under each topic, give unsolicited advice to GCEP.
The three-way competition among secondary fuels

In a carbon-constrained world, $H_2$ is in many three-way competitions: with electricity and with carbon-carrying secondary fuels (gasoline and diesel, aviation fuels, distributed natural gas).

The outcomes of these competitions will depend on further competitions at the point of use:

- engines vs fuel cells vs batteries for motive power
- furnaces vs heat pumps vs electric resistive heating vs solar heating for space heating.
Hydrogen vs carbon-carrying secondary fuels

Relative to carbon-carrying secondary fuels:

H₂ use will not add carbon to the atmosphere – when produced from carbon-free primary energy (renewable or nuclear) or from fossil fuels with carbon capture and storage. [Exception: carbon fuels from biomass do not add carbon to the atmosphere either.]

H₂ may burn more cleanly in combustion engines.

H₂ is better matched to a fuel cell. It is credible that fuel cells will transform the energy system.

H₂ may compete poorly for home heating and personal transport, because of safety constraints on H₂ indoors.
Hydrogen vs electricity

Relative to electricity:

H$_2$ is a fuel.

Historically, fuels have competed well with electricity. Today only one third of primary energy produces electricity. Electric transport has found a role only in trains and vehicles of short range. Electric heating has found a role largely in mild climates.

An all-electric economy is a conceivable outcome of a carbon-constrained world, but it will require dramatic advances in energy storage and heat pumps.

The carbon constraint is neutral between H$_2$ and electricity.
The Case for Hydrogen

1. Most of the century's fossil fuel carbon must be captured.

2. About half of fossil carbon, today, is distributed to small users – buildings, vehicles, small factories.

3. The costs of retrieval, once dispersed, will be prohibitive.

4. An all-electric economy is unlikely.

5. An electricity-plus-hydrogen economy is the most likely alternative.

6. Hydrogen from fossil fuels is likely to be cheaper than hydrogen from renewable or nuclear energy for a long time.
Capture the Carbon in Fossil Fuels
Separate the energy content from the carbon content
Produce two C-free secondary energy carriers:
electricity and H₂
The Carbon Refinery

The importance of hydrogen for distributed uses leads to an energy system that:

– produces hydrogen centrally from fossil fuels, while capturing carbon
– distributes hydrogen to end users and carbon dioxide to storage sites through two new infrastructures
– uses hydrogen productively at end use

The coal power plant, the petroleum refinery, and the natural gas “refinery” converge at the *Carbon Refinery*. The carbon refinery produces a variety of fuels and chemicals, exports electricity, and captures CO$_2$. Over time, a larger fraction of the product is H$_2$. 
The Wabash River
Coal Gasification Repowering Project
Captured Carbon: Stored How?

Storage forms:
1. CO$_2$ as a dense ("supercritical") fluid
2. CO$_2$ in aqueous solution
3. solid graphite
4. carbonate minerals
5. biological materials

Storage locations:
1. deep below ground (including deep below the ocean floor)
2. in hydrocarbon (oil, gas, coal) formations
3. deep in the ocean
4. very deep on the sea floor
5. above ground
6. below ground in soil
CO$_2$ Infrastructure Studies

Natural CO$_2$ fields in southwest U.S.

- McElmo Dome: 0.4Gt(C) in place
- Pipeline from McElmo to Permian Basin: 800 km

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.
Near McElmo Dome, Colorado  (from David Hawkins, NRDC)

“A sign about every quarter-mile” in the Canyons of the Ancients National Monument, Southwest Colorado.
Start Now to Gain Experience with the Permitting of Storage Sites

• Public approval – Openness, fairness, vigilance, responsiveness

• Goals – What constitutes victory? Retention time of 500 years?

• Storage integrity – Escape of CO₂ from a few sites is inconsequential. How can permitting include permission to fail?

• Site-specific issues – Local risks to health (drinking water), property (earthquakes), environment (vegetation). Ownership and liability.

• Co-sequestration – Can co-capture and co-storage allow avoidance of pollution controls (S, N, Cl, Hg)?

• Learning – Embed science in first projects. Instrumentation for model verification, hazard assessment, leak detection, generalization.

Uncertainties of permitting could dominate total sequestration costs.
Unsolicited advice #2

In developing your research agenda, give a prominent role to hydrogen production from fossil fuels with CO$_2$ capture.

Hydrogen from fossil fuels is strikingly underemphasized in this workshop.
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Under each topic, give unsolicited advice to GCEP.
Benchmark: IGCC Electricity with CO₂ Capture

- Cost: 6.4 ¢/kWh. Efficiency: 34.8% (HHV). Assumes 70 bar gasifier with quench cooling. Plant scale is 368 MWₑ.
• Replace syngas expander with PSA and purge gas compressor.
Conventional $H_2$ Production with $CO_2$ Capture

- $H_2$ cost: 7.5 $/GJ$ (HHV). Assumes 70 bar gasifier with quench cooling. Plant scale is 1210 MW$_{th}(H_2)$ (HHV). Byproduct electricity is 4.6 ¢/kWh.
Capture (and Co-sequester) $H_2S$ with $CO_2$

- Remove the traditional acid gas recovery (AGR) unit.
Conventional $H_2$ Production with $CO_2/H_2S$ Capture

- Resulting system is simpler and cheaper.
Produce “Fuel Grade” H₂ with CO₂/H₂S Capture

- Remove the PSA and gas turbine; smaller steam cycle.
“Fuel Grade” (~93% pure) $H_2$ with $CO_2/H_2S$ Capture

- Simpler, less expensive plant. No novel technology needed.
• Use membrane to separate H₂ from the syngas instead of CO₂.
Employ a $\text{H}_2$ permeable, thin film (10 $\mu$m), 60/40% Pd/Cu (sulfur tolerant) dense metallic membrane, configured as a WGS membrane reactor.
Membrane base case is for a Pd/Cu membrane.
Hydrogen System  (Joan Ogden)

Fossil Energy Complex

Fossil Feedstock

- NG, coal

Plant design, scale, P,T, purity of H₂, CO₂

Electricity

- amount, price

H₂ Demand Center

- (Local Pipeline network and refueling stations serving H₂ vehicles)

Geographic density of demand,
Scale, H₂ pressure, H₂ purity, time variation

H₂

length

CO₂ Sequestration Site

- injection wells and assoc. piping

- Well depth, reservoir permeability, layer thickness, pressure, capacity, CO₂ purity
**Base Case System**

**Fossil Energy Complex**  
1000 MW H2

**H2 Demand Center**  
Density = 750 H2 cars/km²  
(=50% of density in LA area)

**H2 pipeline**  
6.8 MPa inlet; >1.4 MPa outlet,  
99.999% purity, 100 km,  
diameter = 0.4 m

**Supercritical CO2 pipeline**  
15.0 MPa inlet, 10 MPa outlet  
95% purity; 100 km; pipeline diameter = 0.3 (0.4) m for NG (coal)

**Electricity** (30 MW, coal only)

**CO2 Sequestration Site**  
2 km well depth, >50 mD perm, 50 m reservoir layer thickness,  
injection radius=6 km  
5000 tCO2/d for NG->H2 plant 2 wells  
10,000 tCO2/d for coal->H2 4 wells

**Local Pipeline network**  
25-28 km  
"spokes" w/10 refueling sta. each  
Pipe diam=0.1 m; Press=1.4-6.8 MPa  
250 refueling stations serving  
1.4 million 82 mpge H2 vehicles; H2 delivered to cars at 34 MPa

**Fossil Feedstock**  
NG or coal
Economics of Base Case System

Capital Cost (million $)

Delivered H2 Cost ($/GJ)
LOCAL H₂ PIPELINE DISTRIBUTION

Assume All Light Duty Vehicles Use H₂, and Threshold for Building a H₂ Local Pipeline is 200 Cars/km²

Columbus, Cleveland, Cincinnati could each support a large coal H₂ plant dedicated to fuel production.

Many smaller cities have demand dense enough for local H₂ distribution, but not large enough for their own coal H₂ plant. Make H₂ at smaller scale (from NG or elec) or pipe or truck H₂ to these cities.
Unsolicited advice #3

Investigate materials, catalysts, and sensors that can improve hydrogen production from fossil fuels.

Investigate retail delivery of hydrogen.

Seek technological insights into hydrogen safety.
Outline of talk

1. The global carbon as a problem of benefits and costs of avoiding carbon build-up to various levels and at various rates.

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4. Achieving stabilization “slice by slice.”

Under each topic, give unsolicited advice to GCEP.
Urgency depends on the stabilization target

- Tougher CO₂ target
- Easier CO₂ target

Expected with effort (BAU)

Graph showing emissions from 2000 to 2100 with different targets.
15 “slices”

A “slice” is an activity that reduces the rate of carbon build-up in the atmosphere and that grows in 50 years from zero to 1.0 Gt(C)/yr.
### Achieving stabilization, slice by slice (p.1 of 2)

<table>
<thead>
<tr>
<th>Mitigation</th>
<th>1 Gt(C)/yr Global Business</th>
<th>Risk, Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal plant: CO₂ stored, not vented</td>
<td>700 1GW plants</td>
<td>CO₂ leakage</td>
</tr>
<tr>
<td>Nuclear displaces average plant</td>
<td>1500 1 GW plants (5 x current)</td>
<td>Nuclear proliferation and terrorism, nuclear waste</td>
</tr>
<tr>
<td>Wind displaces average plant</td>
<td>150 x current</td>
<td>Regional climate change?, NIMBY</td>
</tr>
<tr>
<td>Solar PV displaces average plant</td>
<td>2000 x current; 5x10⁶ ha</td>
<td>Minimal</td>
</tr>
<tr>
<td>Hydrogen fuel</td>
<td>1 billion H₂ cars (CO₂-emission-free H₂) displace 1 billion 30 mpg gasoline/diesel</td>
<td>H₂ infrastructure; H₂ storage</td>
</tr>
<tr>
<td>Efficiency, overall</td>
<td>8% of 2050 “expected” fossil C extraction</td>
<td>Minimal</td>
</tr>
<tr>
<td>Efficiency, vehicles only</td>
<td>2 billion gasoline and diesel cars at 60 mpg instead of 30 mpg (or, at 30 mpg, going 6,000 rather than 12,000 miles per year).</td>
<td>Lifestyle (car size and power) Urban design</td>
</tr>
</tbody>
</table>

**Reductions, for tough limits, by 2050 = ~ 6 Gt(C)/yr**
### Mitigation 1 Gt(C)/yr Global Business | Risk, Impact
---|---
Geological seq’n | 3500 Sleipners, at 1 Mt( CO₂)/year | Global and local leakage
Land sink | Now 1.5 Gt(C)/yr, sink becomes 2.0 Gt(C)/yr, rather than 1.0 Gt(C)/yr | Current estimate for 2050 sink is several times more uncertain
Biomass fuels from plantations | 100x10⁶ ha, growing @ 10 t(C)/ha-yr | Biodiversity, competing land use (200x10⁶ ha = US agricultural area)
Storage in new forest | 500x10⁶ ha, growing @ 2 t(C)/ha-yr | Biodiversity, competing land use

### Achieving stabilization, slice by slice (p.2 of 2)

Reductions, for tough limits, by 2050 = ~ 6 Gt(C)/yr
## Examples of “solution science”

<table>
<thead>
<tr>
<th>Technological solution</th>
<th>Environmental issues at scale-up</th>
<th>Enabling science</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Renewable electricity</strong></td>
<td>Wind and regional climate Albedo modification</td>
<td>PV thin films</td>
</tr>
<tr>
<td><strong>Biofuels</strong></td>
<td>Residues: Nutrient needs of soils Plantations: air emissions</td>
<td>Genomics for ( \text{H}_2 ) from ( \text{H}_2\text{O} )</td>
</tr>
<tr>
<td><strong>Fossil carbon capture/storage</strong></td>
<td>CO(_2) leakage from aquifers Deep ocean CO(_2) retention</td>
<td>( \text{H}_2 ) production, storage, safety, use Co-capture, co-storage (e.g., C + S) Mining, reactivity of silicates</td>
</tr>
<tr>
<td><strong>Unconventional hydrocarbons</strong></td>
<td>Methane clathrate stability</td>
<td>Clathrate physical chemistry</td>
</tr>
<tr>
<td><strong>Nuclear energy</strong></td>
<td>Uranium from seawater</td>
<td>Non-proliferation: Pu, ( \text{U}^{235} ) enrichment Fusion, fusion-fission hybrids</td>
</tr>
<tr>
<td><strong>Direct capture of CO(_2) from air</strong></td>
<td>Regional climate</td>
<td>Absorbers</td>
</tr>
</tbody>
</table>
Unsolicited advice #4

Deepen our understanding of “slices.”

Specifically, pursue “solution science.” That is, address the feasibility, risks, and costs of technological "solutions" that mitigate climate change at significant scale.
Summary of Unsolicited Advice

1. Incorporate environmental science into your research program.

2. Give a prominent role to hydrogen production from fossil fuels with CO$_2$ capture.

3. Investigate materials, catalysts, and sensors that can improve hydrogen production from fossil fuels. Investigate retail delivery of hydrogen and hydrogen safety.

4. Deepen our understanding of the feasibility, risks, and costs of technological "solutions" that mitigate climate change at significant scale.
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