Energy Equals Managing Carbon Cleanly
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A talk on the occasion of receiving the 2003 Leo Szilard Lectureship Award from the American Physical Society

Philadelphia, PA
April 7, 2003
Szilard, Pugwash, 1961

I met Leo Szilard once. We were together at the Pugwash meeting, Stowe, Vermont, September 1961. During that meeting the Russians exploded a 56 metagon H-bomb in the atmosphere, history’s largest atmospheric test of a nuclear weapon.

Szilard commandeered a personal secretary as soon as he arrived, and he dictated correspondence throughout the meeting. He was battling cancer. I recall that a Russian participant brought him a natural remedy.

About to start my second year in graduate school, I had wangled an invitation, as a “driver.” My duties included taking Linus Pauling to the dentist and picking up I. I. Rabi, I think with Szilard, at the local airport.
Energy and environment: Relative to arms control, the other route

In my twenties, seeking domains where societal problems are illuminated by physics, I found only Arms Control, Szilard’s world. It was not for me: I was not happy learning about weapons. In 1969, I found the world of Energy and the Environment.

Energy and the Environment contains a big idea: *The Earth is vulnerable to aggregate human activity.* This idea is generating profound changes in our understanding of the human condition.

The impact of this idea will be comparable to the impact of the idea that nuclear energy can be harnessed.
Goals of this talk

1. To explain what is so very interesting about global carbon management.

2. To recruit physicists into the field by identifying several open areas requiring fresh thinking.
What if the fossil fuel future is robust, but the Greenhouse problem is severe?

<table>
<thead>
<tr>
<th>Will the Greenhouse problem wither away?</th>
<th>Will the fossil fuel system wither away?</th>
</tr>
</thead>
<tbody>
<tr>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>A nuclear or renewables world unmotivated by climate.</td>
<td>Assumed by most people in the fuel industries and most of the public</td>
</tr>
<tr>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>Assumed by most environmentalists</td>
<td>OUR WORKING ASSUMPTIONS</td>
</tr>
</tbody>
</table>
The Rosetta Stone

1 ppm(v) = 2.1 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 CO₂. A year from now, therefore, about 373 of every million molecules will be CO₂, if there are no removal mechanisms (“sinks”).

There are sinks, both land and ocean sinks. Today they remove CO₂ from the atmosphere at about half the rate that we are adding CO₂.

http://www.eia.doe.gov/emeu/international/total.html#IntlCarbon
Atmospheric CO₂ Concentration with and without 1980-99 sinks

“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.
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 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.
Generic Production of Hydrogen, Electricity, and CO₂ from Fossil Fuels

Feedstock (natural gas, petroleum residuals, tar sands, coal, etc.)

Fuel Reformer (Gasifier, partial oxidizer, steam reformer, etc.)

Air Separation Unit

Oxygen Compressor

Feedstock Pressurization

Air

N₂

O₂

Pressurization

Compressed Oxygen

Hydrogen Compressor

Heat Recovery, Syngas Cleanup

Water-Gas Shift Reactor

CO₂, H₂, CO₂, H₂O

Syngas

CO₂, H₂, CO₂, H₂O

Electrical Production (combustion in air or O₂, electric power from steam or gas turbine)

Compressed Oxygen

Purge gas/raffinate

CO₂, H₂O, some H₂

Gas Separation (solvent absorption+PSA, membrane, etc.)

Majority of H₂ (relatively pure)

CO₂ Dryer/Compressor

CO₂ (+SO₂ optional)

Supercritical CO₂ for sequestration (optional sulfur co-sequestration)

H₂, CO₂, H₂O

Majority of H₂ (relatively pure)

Hydrogen Compressor

H₂ pipeline

Electrical Power

H₂ pipeline

H₂ pipeline
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

Color: Current projects
Near McElmo Dome, Colorado (from David Hawkins, NRDC)

“A sign about every quarter-mile” in the Canyons of the Ancients National Monument, Southwest Colorado.
Urgency depends on the stabilization target.

Expected with effort (BAU)

Easier CO₂ target

Tougher CO₂ target
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.
Evolutionary and revolutionary solutions

Examples of evolutionary solutions

Efficiency
Coal gasification with CO$_2$ capture and geological storage
Wind, photovoltaics
Biofuels and biological storage

Examples of revolutionary solutions

Fusion
Inorganic photosynthesis
Direct capture from air
Storage as carbonates

We need, side by side, to deploy evolutionary solutions and to develop revolutionary solutions. For both, we need “solution science.”
## 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>
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<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>
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Reductions, for tough limits, by 2050 = ~ 6 Gt(C)/yr
Achieving stabilization, slice by slice (p.2 of 2)

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<th>1 Gt(C)/yr Global Business</th>
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<tr>
<td>Geological seq’n</td>
<td>3500 Sleipners, at 1 Mt( CO₂)/year</td>
<td>Global and local leakage</td>
</tr>
<tr>
<td>Land sink</td>
<td>Now 1.5 Gt(C)/yr, sink becomes 2.0 Gt(C)/yr, rather than 1.0 Gt(C)/yr</td>
<td>Current estimate for 2050 sink is <em>several</em> times more uncertain</td>
</tr>
<tr>
<td>Biomass fuels from plantations</td>
<td>100x10⁶ ha, growing @ 10 t(C)/ha-yr</td>
<td>Biodiversity, competing land use (200x10⁶ ha = US agricultural area)</td>
</tr>
<tr>
<td>Storage in new forest</td>
<td>500x10⁶ ha, growing @ 2 t(C)/ha-yr</td>
<td>Biodiversity, competing land use</td>
</tr>
</tbody>
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Reductions, for tough limits, by 2050 = ~ 6 Gt(C)/yr
Eight Enduring Open Problems in Energy and the Global Environment

I am confident (April 2003) that these eight problem areas are robust: in each area, over the next several decades our understanding will deepen. Each will reward effort.

1. The relative priority of mitigating global change
2. Consumption and culture
3. The competitiveness of non-traditional fossil fuels
4. Public acceptance of CO$_2$ storage
5. The viability of hydrogen
6. Environmental effects of large-scale renewables
7. The internationalization of nuclear power
8. The governance of geoengineering
Enduring Problem 1

1. The relative priority of mitigating global change. Global change competes for attention with urban air pollution, the loss of biodiversity, intrusion on wilderness, workplace safety and health, poverty, and other challenges. Mitigating global change competes with adapting to global change.

Needed:

A. Better understanding of what is at stake in climate change.

B. Clarification of synergisms and incompatibilities across objectives. Example: Reducing global carbon emissions is fully compatible with meeting “basic human needs.”
Enduring Problem 2

2. *Consumption and culture.* Today, arguably, there is a single ladder of consumption, from the poor to the super-rich, everyone aspiring to climb at least one rung. Will alternative views of the good life emerge, leading to multiple ladders?

*Needed:*

A. *Technological innovations addressing end-use efficiency.* *(A good example from the 1970s was work on window coatings.)*

B. *More insightful quantitative decomposition of consumption.* *(A good example is the decomposition of travel by purpose of trip.)*
3. The competitiveness of non-traditional fossil fuels. Fossil fuels can dominate the energy system for at least a century, long after traditional oil and gas retreat. Coal can dominate, or, alternately, non-traditional liquid and gaseous hydrocarbons. Just beyond the planning horizon are the methane clathrates – methane molecules locked in water or ice matrices under pressure. Methane clathrates are abundant, but also dangerous.

Needed:

A) Field, laboratory, and theoretical studies of clathrates.

B) Special attention to major unintended releases of methane.

C) Investigation of CO$_2$ disposal in clathrates.
Enduring Problem 4

4.  \textit{CO}_2 \textit{storage and public acceptance}. Scientists contributed to the impasse on nuclear wastes by promising perfect containment. Must \textit{CO}_2 \textit{storage} founder as nuclear power has? Can an impasse be avoided by choosing goals and assessing risks via processes that revise the relationship between experts and the public?

\textit{Needed:}

\begin{itemize}
  \item [A)] Pilot projects that focus public attention on the licensing and operation of \textit{CO}_2 \textit{storage facilities}.
  \item [B)] Technological innovations in site characterization and monitoring.
\end{itemize}
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 eliminate much of the cost of above-ground pollution control (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.
Enduring Problem 5

5. *The viability of hydrogen.* Hydrogen is widely used in industry, but there is considerable uncertainty about its compatibility with ordinary life. Safety and storage are dominant concerns.

*NEEDED:*

A) *Breakthroughs in storage via new materials*

B) *Technological insights into hydrogen safety.*
Enduring Problem 6

6. Environmental effects of large-scale renewables  Deeply substituting renewable energy for fossil fuels to reduce climate impacts can be counterproductive. What matters is how large-scale extraction of renewable energy (from wind, waves, falling water, ocean thermal gradients, biomass) affects other aspects of the environment.

Needed:

A) Field, laboratory, and theoretical studies of a modified Earth, where renewable energy is extracted at a rate sufficient to affect global carbon significantly.

B) Environmentally sensitive designs of large-scale renewable energy systems to minimize adverse impacts.
Enduring Problem 7

7. Nuclear power and international institutions Nuclear power is a promise unfulfilled. Of its deficiencies, the couplings of civilian and military applications are the most intractable. Internationalization of parts of the fission fuel cycle (uranium enrichment, plutonium management) may be required for revival. Nuclear fusion power, if commercialized, will face similar challenges (e.g., the fusion-fission hybrid that breeds Pu).

Needed:

A) Institutional inventions that address the present incompatibility of a desirable international order and global commercialization of nuclear power.

B) Reactor and fuel cycle designs consistent with selective internationalization.
Leo Szilard was probably the first person in the world to become firmly convinced that it would be possible to build an atomic bomb. Fearing that scientists in Nazi Germany might build the weapon, Szilard persuaded Albert Einstein to write to President Franklin D. Roosevelt in August 1939 about the possibility of the United States building an atomic bomb. Szilard made important contributions to the Manhattan Project, but he opposed the use of the bomb against Japan, and after the war he helped found organizations that since that time have been actively promoting nuclear arms control — the Federation of American Scientists and the Council for a Livable World.

“...the element uranium may be turned into a new and important source of energy in the immediate future. Certain aspects of the situation which has arisen seem to call for watchfulness and, if necessary, quick action on the part of the Administration.”

_Einstein to Roosevelt, August 2, 1939_
Enduring Problem 8

8. Geoengineering and governance Today’s environmentalism seeks the minimization of human impact. Within view is a more aggressive ideology, geoengineering, which seeks maximization of human welfare. Human beings will intervene to prevent the next ice age. We are unprepared for geoengineering, much as we are unprepared for the engineering of the human genome.

Needed:

A) Vivid examples that facilitate discussion of the governance of global change: Who decides ends and means?

B) Incorporation of governance into global change mitigation strategies. Example: parallel development of technologies and licensing rules for CO₂ storage.
Robert Frost

*Two Tramps in Mud Time*

(opening stanza)

Out of the mud two strangers came
And caught me splitting wood in the yard.
And one of them put me off my aim
By hailing cheerily "Hit them hard!"
I knew pretty well why he dropped behind
And let the other go on a way.
I knew pretty well what he had in mind:
He wanted to take my job for pay.
Nothing on either side was said.
They knew they had but to stay their stay
And all their logic would fill my head:
As that I had no right to play
With what was another man's work for gain.
My right might be love but theirs was need.
And where the two exist in twain
Theirs was the better right -- agreed.
But yield who will to their separation,
My object in living is to unite
My avocation and my vocation
As my two eyes make one in sight.
Only where love and need are one,
And the work is play for mortal stakes,
Is the deed ever really done
For Heaven and the future's sakes.