Systems analysis of CO₂ capture technologies: Developing economy-wide thermodynamic metrics

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Source: saskpowerccs.com
Source: Sweeney Smith (2014)

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Motivation

• Applying CCS at scale would require economy-wide shifts in material and energy flows
• Designs should minimize capital investment, material consumption, and energy penalties
• Avoid unintended consequences ("backfire") elsewhere in economy or biosphere

Properly assessing CCS technologies requires:

1. Understanding economy-wide environmental impacts

2. Comparing diverse environmental outcomes
Goal 1: An economy-wide perspective

- **Life cycle assessment (LCA)** models economy-wide environmental impacts
- Tracks flows of natural resources into and pollutants out of each process

Supply chains are actually deeply interconnected “supply webs”
Goal 2: Comparing diverse environmental impacts

• How should we trade off different environmental impacts?
  – Different media: water vs. air?
  – Different time scales: now vs. future?
  – Different health or ecosystem impacts: acute vs. chronic?

• Long-standing problem in environmental assessment
  – Many schemes proposed, consensus lacking

• Exergy has been proposed as a unified thermodynamic measure of potential harm from effluents

Sources: Szargut (1985); Crane et al. (1992); Ayres et al. (1996, 1998); Seager and Theis (2002); Simpson and Edwards (2011); Dincer and Rosen (2012)
Exergy is...

• ... the maximum amount of work that can be extracted from a system containing a resource which is out of equilibrium with an environment

• ... a measure of potential for change as the resource equilibrates with the (unchanging) environment

• ... the “useful” part of energy

• ... variable depending on nature of disequilibrium:

<table>
<thead>
<tr>
<th>Kinetic</th>
<th>Gravitational</th>
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</thead>
<tbody>
<tr>
<td>Thermomechanical</td>
<td>Nuclear</td>
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<tr>
<td>Chemical</td>
<td>Radiative</td>
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A process takes in exergy in natural resources and other products, outputs exergy as product and wastes.
Methods: Developing an economy-wide exergy model

- **Ecoinvent** life cycle analysis dataset (Swiss ETH since 1992)
- Connected set of ~10,000 physical processes
  - 1,700 flows of wastes and resources to and from environment
- Exergy-relevant quantities are not always recorded in the dataset
  - Pre-analyze to prioritize flows
  - Shows that only 100s of processes and flows must be modeled
  - Exergy conversion matrix $X$

Source: Sweeney-Smith and Brandt (2015), Sweeney-Smith (2014)
Methods: analyzing a baseline CCS system

- Model the NETL baseline CCS system
- Model and size all reactors and process units, detailed materials bill
- Use NETL data where possible as this is a “standard” plant

Source: Sun (2015), Sun and Brandt (2015)
Exergy inputs and outputs for the baseline system

Exergy flows (TJ)

Coal

Nat. res.

Exergy flows (PJ)
Exergy inputs and outputs for the baseline system

Exergy flows (TJ)

Coal

Nat. res.

Destr.

Waste

Elec.
Exergy inputs and outputs for the baseline system

<table>
<thead>
<tr>
<th></th>
<th>At plant (HHV)</th>
<th>Econ-wide (Exergy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>37%</td>
<td>23%</td>
</tr>
<tr>
<td>w/ CCS</td>
<td>26%</td>
<td>17%</td>
</tr>
</tbody>
</table>

Expend 50 units of natural resource exergy for every unit pollution reduced.
• Exergy measures disequilibrium with an **unchanging** reference environment

• A poor model of CO$_2$ impacts
  – CO$_2$ **builds up** over centuries and **changes** reference environment
  – Changes energy balance of Earth’s (driven, non-equilibrium) climate system
  – Affects ecosystems (e.g. ocean acidification)

• Propose augmenting with **time-integrated exergetic impact** (TEI)
Long-term energy and exergy impacts of CO$_2$

Zhang and Caldeira (2015):
- 4.5 x $10^{10}$ J of total warming per mole of CO$_2$
- ~100,000 times heating value of C

Conceptualized here as increase in thermal input to human and biological systems from atmosphere, relative to baseline

First estimate of \textit{time-integrated exergetic impact}
First estimate of *time-integrated exergetic impact*

Add thermal energy at $\Delta T = 1.5$ K

- Investing exergetic resources in capturing CO$_2$ reduces exergy flows to future human/biosphere by $\sim 600x$
Does thermodynamic quality of env. impacts matter?

A: Current lightning

10 cloud-ground flashes/sec

Each flash dissipates ~1 GJ
(10-100C, 10s-100s MV)

Power ~ $10^{10}$ W

B: Current climate change

Radiative forcing due to CO$_2$ is
1.7 W/m$^2$ (rel. to 1750)

Area of earth = 5.1 x$10^{14}$ m$^2$

Power ~ $10^{15}$ W

If same energetic forcing from CO$_2$ manifested as charge buildup,
natural rate of lightning would have to increase about $100,000x$
Ecosystem impacts

• Unclear how to measure CO\textsubscript{2} impact on ecosystems using thermodynamics

• Chemical exergy is a poor indicator of biological impacts:
  – Canola oil: 40.6 MJ/kg
  – Sodium cyanide: 13.7 MJ/kg

• Various methods have been used to understand thermodynamics of biology

• Does exergy measure what we care about?

Source: Morowitz (1968), Jorgensen et al. (2004, 2006)
Conclusions

• Holistic environmental assessment of new energy technologies is possible
  – Can cover all processes in economy and measure impacts on consistent basis

• Traditional exergy analysis of CO$_2$ impacts makes benefits of CCS look small

• Extended impact analysis must include long-term changes
  – CO$_2$ pollution impacts likely dramatically outweigh useful work required to abate CO$_2$
  – Thermodynamic quality of environmental impacts matters

• Numerous applications for systems-scale thermodynamic comparisons of other energy tech.