Carbon Capture

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Princeton University
Activities

• \( \text{H}_2 / \text{electricity production} \)
  - Membrane reactors
  - Incremental modifications of conventional technology
  - \( \text{H}_2 \) production with co-sequestration of sulfur (\( \text{H}_2 \text{S} \) or \( \text{SO}_2 \)) and \( \text{CO}_2 \).

• \( \text{H}_2 / \text{CO}_2 \) infrastructure

• \( \text{H}_2 \) combustion

• Princeton-Tsinghua collaboration on low emission energy technologies for China

• \( \text{H}_2 \) utilization technologies
Differences in Propagation Mode between Lean Hydrogen-Air and Propane-Air Flames

- Above result suggests the potential to suppress the tendency for a hydrogen-air mixture to self accelerate and detonate by adding a hydrocarbon.

Sequence of an expanding spherical lean hydrogen-air flame, showing the phenomena of flame surface wrinkling and self-acceleration.

Sequence of an expanding spherical lean propane-air flame, showing the absence of flame surface wrinkling and self-acceleration.

Princeton Tasks

• Polygeneration process design and cost modeling: DME,F-T liquids, methanol, H₂, syngas, chemicals, heat, electricity.
• Carbon sequestration analysis for near-term EOR and CBM; aquifer CO₂ storage for long term.
• Integrated strategic analysis.

Tsinghua Tasks

• Energy-data collection for Yanzhou and Jincheng.
• Coal-based polygeneration process design, simulation.
• Lifecycle environmental impact and cost analysis.
• Integrated strategic analysis.
• Outreach to Yangzhou Mining Group Ltd., Shanxi Jincheng Anthracite Coal Mining Group Ltd., and other decision makers.
Renewables/Fossil Energy Competition, Carbon-Constrained World

- For electricity, renewables will be strong competitors to decarbonized fossil fuels
  - Esp. for wind (central station), PV (distributed, grid-connected)
  - Large-scale electric storage problem solved (CAES)

- Poor economic prospects for making $\text{H}_2$ via electrolysis/thermochemical cycles from renewables for markets that use fuels directly (2/3 of $\text{CO}_2$ emissions today)—relative to $\text{H}_2$ from fossil fuels with $\text{CO}_2$ removal/sequestration
Implications of Renewable/Fossil Energy Competition for Carbon Management

• No carbon problem if fossil fuels = conventional oil/NG
• Serious carbon problem if coal, tar sands, heavy oils, unconventional NG are consumed as “fuels used directly” w/o decarbonization, even if electricity 100% decarbonized
• But gasification-based $\text{H}_2$ production/$\text{CO}_2$ sequestration technologies offer good prospects for decarbonizing low-quality fossil energy feedstocks at attractive costs
• Residuals gasification at refineries: promising early step on path to large-scale gasification-based $\text{H}_2$ production
“Conventional Technology” \( \text{H}_2 \) Production with \( \text{CO}_2 \) Capture

1. **Air separation unit**
   - Air
   - Oxygen
   - \( \text{CO}_2 \)-lean exhaust gases

2. **Gasifier**
   - Coal slurry
   - CO-rich raw syngas

3. **Quench + scrubber**
   - CO-rich raw syngas

4. **High temp. WGS reactor**
   - Syngas expansion

5. **Syngas cooling**
   - Steam

6. **Low temp. WGS reactor**
   - \( \text{H}_2 \) and \( \text{CO}_2 \)-rich syngas

7. **Pressure swing adsorption**
   - \( \text{H}_2 \) product
   - Compressed purge gas

8. **CO\(_2\)/H\(_2\)_S physical absorption**
   - \( \text{CO}_2 \) and \( \text{H}_2 \)_S
   - Lean solvent
   - Rich solvent

9. **Solvent regeneration**
   - \( \text{CO}_2 \) + \( \text{H}_2 \)_S to storage

**Additional Points**

- \( \text{H}_2 \) production
- \( \text{CO}_2 \) capture
- \( \text{O}_2 \) for NO\(_x\) control
- \( \text{N}_2 \) for NO\(_x\) control

Conventional hydrogen 2 (1-7-02)
• With CO₂ venting, cost of H₂ from NG SMR always lower than H₂ from coal
• But, even at today’s low NG prices (2.44 $/GJ → 2.96 ¢/kWh), H₂ from coal with CO₂-sulfur co-sequestration is comparable to H₂ from NG
• Note: 70 bar conventional technology is commercially available today
At higher NG prices (3.4 $/GJ HHV $\rightarrow$ 3.59 c/kWh), cost of H$_2$ from coal with CO$_2$-sulfur co-sequestration is significantly lower than H$_2$ from NG SMR.

Caveats: 1) NG SMR analysis not ours, 2) some benefits from ATR expected.
**HMSR-Based Production of Hydrogen and Electricity**

*Uncooled Raffinate Turbine*

**Conditions:**
- \( \frac{H_2O}{C} = 2.56 \)
- 85% absolute \( H_2 \) recovery
- *Input coal*: 1.5 GW\(_{th}\) HHV
- *Output \( H_2 \)*: 1 GW\(_{th}\) HHV
- *Output net electricity*: 12 MW\(_e\)

*Effective \( H_2 \) Conversion Efficiency* \((= 100 \times [H_2 \text{ out}] / [\text{coal feed} - \text{coal saved}])\) = 69.0% (HHV)

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CMI slide uncooled turbine 4 (#93) (1-9-02)
• Increasing pressure can significantly reduce cost of decarbonized hydrogen
• Cooled raffinate turbine typically requires low HRF to realize high TIT
• Uncooled turbine/high H₂ recovery: greater promise, esp. at low elec. prices
Component Capital Cost Estimates

- Significant variation found in cost values, methodology, and depth of detail
- Our cost model consists of a self-consistent set of values from the literature
- Cost database is evolving; less reliable values removed; range is narrowing
Lessons Learned—Year 1
Major Technical Findings

• Optimal H$_2$ plant makes electricity coproduct—sensitive to electricity price
• Higher gasifier pressure $\Rightarrow$ lower H$_2$ cost
• Co-sequestration of S (H$_2$S or SO$_2$) with CO$_2$ $\Rightarrow$ substantial cost reduction—viable?
• Relative merits of HSMR & conventional gasifier-based technologies unclear
Lessons Learned—Year 1

Integrated Cost Analysis

Costs ($/GJ) of H₂ production from coal and NG

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<th>Feedstock</th>
<th>Feedstock cost</th>
<th>Vented</th>
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<td>7.4</td>
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<tr>
<td>NG</td>
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<td>5.8</td>
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Carbon tax ($/tC) needed to induce sequestration

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<th></th>
<th>Natural Gas</th>
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Lessons Learned—Year 1
Strategic Considerations

• Near-term opportunity: gasify petroleum residuals at refineries to make $H_2$. For petcoke @ $10/t, H_2$ cost same as for SMR and $2.5/GJ$ NG
  – CO2 coproduct much cheaper than from SMR…EOR opportunities?

• Feedstocks for gasification in longer term: heavy oils, tar sands, coal—delivered to city gate “carbon refineries” for $H_2$ manufacture