Hydrogen from Coal

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Mitretek Systems
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Content

- Drivers & Issues
- Current hydrogen from coal technology
- Coproduction of hydrogen and power from coal
- Carbon dioxide implications
- Advanced SOFC configuration for hydrogen and power production from coal
- Comparison with natural gas
- Challenges
Issues & Drivers for Hydrogen

- ISSUES:
  - low volumetric energy content (storage)
  - Infrastructure for Hydrogen Delivery
  - Carbon capture & Sequestration
  - Resources for Mass Production

- DRIVERS:
  - energy security
  - petroleum resource depletion
  - climate change & pollution
Hydrogen Storage

Hydrogen STP

Gasoline
#H₂ = 7.3, Btu = 853,000

Diesel
#H₂ = 8.3, Btu = 949,000

Methanol
#H₂ = 6.2, Btu = 430,000

Compressed H₂ (6000 psi)
#H₂ = 2, Btu = 110,000

Liquid H₂
#H₂ = 4.4, Btu = 229,000

Metal Hydrides
#H₂ = 3.0, Btu = 160,000

1 Cubic Foot Volume

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Coal Analysis

- Illinois #6 Old Ben #26 Mine:
  - Proximate as-received (wt %)
    - Moisture 11.12
    - Ash 9.7
    - Volatile matter 34.99
    - Fixed carbon 44.19
    - HHV Btu/# 11,666
  - Ultimate as-received (wt %)
    - Moisture 11.12
    - Carbon 63.75
    - Hydrogen 4.5
    - Nitrogen 1.25
    - Chlorine 0.29
    - Sulfur 2.51
    - Ash 9.7
    - Oxygen (bd) 6.88
Financial Assumptions

- 25 year plant life
- 67/33 % debt/equity financing
- 15 % return on equity
- 8 % interest, 16 year term
- 3 % inflation (coal de-escalation of 1.5 % per annum below general inflation)
- 16 year DDB depreciation
- 40 % combined Federal and State tax rate
- 3 year construction, 50 % output in start-up year
- Sequestration of high pressure CO$_2$ stream costs $10/ton carbon
Cases 1 and 2: Hydrogen from Coal

Coal 3000 TPD

Gasification

Raw Shift

Gas Cleaning

CO₂ Removal

PSA

Product Hydrogen

Oxygen

ASU

Air

Air

H₂S

Claus/Scot

Tail Gas

Power Generation

Plant Power

Net Power
## Summary of Hydrogen from Coal Cases

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Carbon Sequestration</td>
<td>NO</td>
<td>YES (87%)</td>
<td></td>
</tr>
<tr>
<td>Hydrogen MMSCFD</td>
<td>131</td>
<td>119</td>
<td></td>
</tr>
<tr>
<td>Coal T/D (AR)</td>
<td>3000</td>
<td>3000</td>
<td></td>
</tr>
<tr>
<td>Efficiency (% HHV)</td>
<td>63.7</td>
<td>59</td>
<td></td>
</tr>
<tr>
<td>XS Power MW</td>
<td>20.4</td>
<td>26.9</td>
<td></td>
</tr>
<tr>
<td>Power Value (MILS/k Wh)</td>
<td>35.6</td>
<td>53.6</td>
<td></td>
</tr>
<tr>
<td>Capital $MM</td>
<td>367</td>
<td>417</td>
<td></td>
</tr>
<tr>
<td>RSP of Hydrogen $/MMBTU</td>
<td>6.83</td>
<td>8.18</td>
<td></td>
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</tbody>
</table>
Case 3: Coal to Hydrogen and Power

Coal 6000 TPD

Gasification → Gas Cleaning → Cooling/Shift → PSA → Hydrogen 149 MMSCFD

Oxygen

ASU

Air

CC Plant → 475 MW

Capital $910MM

COE 35.6 Mills/kWh

Hydrogen RSP $5.42/MMBTU

Efficiency 62.4%

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Case 4: Coal to Hydrogen and Power
(Sequestration)

Coal 6000 TPD

Gasification

Gas Cleaning

Cooling /Shift

CO₂ Removal

PSA

Coal to Sequestration (91%)

ASU

Oxygen

Air

CC Plant

358 MW

Hydrogen 153 MMSCFD

Capital $950MM  H₂ RSP $/MMBTU  COE Mills/kWh  Efficiency 56.5%

5.64  53.6 (Gas CC, sequestration)
6.89  46.3 (Coal IGCC, sequestration)
8.73  35.6 (Coal IGCC, no sequestration)

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## Summary of Coproduction Cases

<table>
<thead>
<tr>
<th></th>
<th>CASE 3</th>
<th>CASE 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Sequestration</td>
<td>NO</td>
<td>YES (95%)</td>
</tr>
<tr>
<td>Hydrogen MMSCFD</td>
<td>149</td>
<td>153</td>
</tr>
<tr>
<td>Coal T/D (AR)</td>
<td>6000</td>
<td>6000</td>
</tr>
<tr>
<td>Efficiency (%HHV)</td>
<td>62.4</td>
<td>56.5</td>
</tr>
<tr>
<td>XS Power MW</td>
<td>475</td>
<td>358</td>
</tr>
<tr>
<td>Power Value (MILS/kWh)</td>
<td>35.6</td>
<td>53.6</td>
</tr>
<tr>
<td>Capital $MM</td>
<td>910</td>
<td>950</td>
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<tr>
<td>RSP of Hydrogen $/MMBTU</td>
<td>5.42</td>
<td>5.64</td>
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</table>
**CO₂ Implications of Coal to Hydrogen and Power (Case 3)**

- **6000 TPD Coal** (3825 TPDC) → **H₂ Production Facility** → **475 MW**
  - 149 MMSCFD H₂ ≡ 358,000 KG ≡ 358,000 Gallons Gasoline
  - ≡ 26 MM Miles (1559 Btu/mile GREET)

- **Natural Gas** (1176 TPDC) 75 MMSCFD → **NGCC Plant** → **475 MW**

- **Petroleum Crude** 7900 BPD (1040 TPDC) → **Refinery** → **358,000 Gallons/Day Gasoline**
  - ≡ 8.7 MM Miles (4678 Btu/Mile GREET)

**Carbon Accounting**

\[
\text{TPD Power} = 1176 \times 2.99 = 3108 \text{ Fuels (Miles EQ)}
\]

\[
4284 \text{ Total} \quad (-11\%)
\]
**CO₂ Implications of Coal to Hydrogen and Power (Case 4)**

- **6000 TPD Coal** (3825 TPDC) → **H₂ Production Facility** → 191 TPDC
- **358 MW**
- **153 MMSCFD H₂ ≡ 368,000 KG ≡ 368,000 Gallons Gasoline ≡ 26.7 MM Miles**

**Natural Gas**
- **56.5 MMSCFD** (886 TPDC) → **NGCC Plant** → 358 MW

**Petroleum Crude**
- **8120 BPD** (1069 TPDC) → **Refinery** → 368,000 Gallons/Day Gasoline ≡ 8.94 MM Miles

**Carbon Accounting**
- **886 Power**
- **1069 x 2.99 = 3193 Fuels (Miles EQ)**
- **4079**
- **Carbon Avoided = 3,888 (TPD) (4.4 MM Tons CO₂/Yr)**
Case 5: SOFC for Power and Hydrogen (Sequestration)

- 151 MW HRSG Steam
- 118 MW Turbine
- 509 MW Net Power
- 358 MW Anode
- 298 MW PSA
- 149 MMSCFD H₂
- 6000 TPD HGCU
- 398 MW CO₂ Removal
- 64.5% Efficiency (HHV)

- Capital $1,037 Million
- COE mills/kWh:
  - 53.6 Gas CC, sequestration
  - 41.3 (Coal IGCC, sequestration)
  - 35.6 (SOFC/sequestration)

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MTS Mittech Systems
Case 6: SOFC Power/H$_2$/Membrane (Sequestration)

- 150 MMSCFD H$_2$
- 6000 TPD Coal
- 1100°F
- H$_2$ 22 Atm
- 8 MW
- HRSG
- H$_2$O
- 200 Bar
- Net Power 519 MW
- COE 53.6 Mills/kWh

Capital $1,019 Million

H$_2$ $$/MMBTU

COE 53.6 Mills/kWh

53.6 Gas CC, sequestration

46.3 (Coal IGCC, sequestration)

41.0 (SOFC/sequestration)

35.6 (Coal IGCC, no sequestration)

Efficiency 65.2% (HHV)

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## Summary of Cases using SOFC Systems

<table>
<thead>
<tr>
<th></th>
<th>CASE 5</th>
<th>CASE 6</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CARBON SEQUESTRATION</strong></td>
<td>YES (90%)</td>
<td>YES (95%)</td>
</tr>
<tr>
<td><strong>HYDROGEN MMSCFD</strong></td>
<td>149</td>
<td>150</td>
</tr>
<tr>
<td><strong>COAL T/D (AR)</strong></td>
<td>6000</td>
<td>6000</td>
</tr>
<tr>
<td><strong>EFFICIENCY (%HHV)</strong></td>
<td>64.5</td>
<td>65.2</td>
</tr>
<tr>
<td><strong>XS POWER MW</strong></td>
<td>509</td>
<td>519</td>
</tr>
<tr>
<td><strong>POWER VALUE (MILS)</strong></td>
<td>53.6</td>
<td>53.6</td>
</tr>
<tr>
<td><strong>CAPITAL $MM</strong></td>
<td>1,037</td>
<td>1,019</td>
</tr>
<tr>
<td><strong>RSP OF HYDROGEN $/MMBTU</strong></td>
<td>2.79</td>
<td>2.40</td>
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</tbody>
</table>
Hydrogen Cost vs Natural Gas Price

- Current Coal (N/S)
- Advanced Coal Coproduction
- Advanced SOFC/Membrane (Seq)

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Challenges

- **Hydrogen Production:**
  - carbon capture & sequestration
  - improved separations & purification

- **Delivery & Storage:**
  - infrastructure
  - volumetric energy density

- **Hydrogen Utilization:**
  - fuel cell compactness & costs