STATUS OF HYDROGEN PRODUCTION WITH CO₂ CAPTURE

- INCLUDING PERSPECTIVES ON EMISSIONS AND SCALE

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Integrated syngas production & gas separation

Protonic Membrane Reformer technology

Today’s solution

Protonic Membrane Reformer (PMR)

Steam Methane Reforming w. CCS (6 steps)

<table>
<thead>
<tr>
<th>Heat</th>
<th>SMR</th>
<th>WGS</th>
<th>CO₂ capture</th>
<th>H₂ Separation</th>
<th>H₂ Compression</th>
</tr>
</thead>
<tbody>
<tr>
<td>NG + Steam</td>
<td>Air</td>
<td>Fuel</td>
<td>Syngas</td>
<td>CO₂</td>
<td>H₂</td>
</tr>
</tbody>
</table>

Process Step reduction

Protonic Membrane Reformer (PMR) technology

- "Tube-in-shell" membrane reactor producing pure H\textsubscript{2} from natural gas
- Membrane wall has three layers:
  - Anode (thickest layer, porous material - BZCY and Ni)
  - Solid electrolyte (dense proton conductor - BZCY)
  - Cathode (porous material - BZCY and Ni)
- High-pressure H\textsubscript{2} is delivered to shell (electrochemical compression)

Low temperature \( \text{CO}_2 \) separation – capture conditions
Low-temperature separation technology

• Vapor–liquid phase separation after compression and cooling of the gaseous mixture
  • Obtainable CO$_2$ capture rate, specific separation and compression work, and thus power consumption, are sensitive to the CO$_2$ concentration of the incoming flue- or syngas

• CO$_2$-enhanced retentate stream ideal incoming stream
• H$_2$-rich off-gas can be partially recycled to the reactor maximizing the overall HRF and CO conversion

Membane + Low temperature process for H₂ & CO₂ production from syngas
ELEGANCY — Enabling a low carbon economy by H₂ and CCS

- Duration: 2017-08-31 to 2020-08-31.
- Budget: 15 599 kEUR
Hydrogen production with CCS

- VPSA promising for process intensification
- New adsorption processes are needed for this separation
- Cycle design for a generic inlet stream and a commercial activated carbon

Anne Streb, Marco Mazzotti, ETH Zurich
Hydrogen production with CCS

• Cycle designs developed for generic inlet stream and optimized for case studies:
  • Steam methane reforming (SMR)
  • Autothermal reforming (ATR)
  • High temperature WGS (HT-WGS)
  • High and low temperature WGS (LT-WGS)

• Lab pilot completed and first experimental results obtained
Cycle D application: Separation performance for different case studies

<table>
<thead>
<tr>
<th>Adsorbent</th>
<th>SMR + HT-WGS</th>
<th>SMR + HT-WGS + LT-WGS</th>
<th>ATR + HT-WGS</th>
<th>ATR + HT-WGS + LT-WGS</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>mol%</td>
<td>75.81</td>
<td>76.2</td>
<td>70.6</td>
</tr>
<tr>
<td>CO₂</td>
<td>mol%</td>
<td>16.31</td>
<td>19.6</td>
<td>19.74</td>
</tr>
<tr>
<td>CH₄</td>
<td>mol%</td>
<td>3.03</td>
<td>3.5</td>
<td>0.34</td>
</tr>
<tr>
<td>CO</td>
<td>mol%</td>
<td>4.65</td>
<td>0.4</td>
<td>9</td>
</tr>
<tr>
<td>N₂</td>
<td>mol%</td>
<td>0.2</td>
<td>0.3</td>
<td>0.24</td>
</tr>
<tr>
<td>Ar</td>
<td>mol%</td>
<td>0</td>
<td>0</td>
<td>0.08</td>
</tr>
</tbody>
</table>

- Very high H₂ purity possible
- H₂ purity limited for ATR: Argon in H₂ product

$r_{CO₂} \geq 0.90$

$\Phi_{CO₂} \geq 0.96$
"Green" or "Blue" hydrogen?
Mythbusting: "Blue hydrogen" vs. "Green hydrogen"

- Up-/mid-stream emissions from natural gas production
- Direct CO₂ emissions from reforming plant (93.4% CO₂ capture)
- Indirect CO₂ emissions from electricity consumption
- Natural gas reforming with 93.4% CO₂ capture + Liquefaction

16.4 kg/MWhₑₐ
Norway average (2017, NVE)
Mythbusting: "Blue hydrogen" vs. "Green hydrogen"
"Green" or "Blue" hydrogen?
= Clean hydrogen?
How large is large is large-scale?
In perspective: 500 ton liquid hydrogen per day

- **820 MW_{HHV}** hydrogen energy flux
- **7 TWh per year** of hydrogen energy output
- Decarbonised fossil route (NG with CCS):
  - < 1 % of annual Norwegian natural gas production
- Renewable route (electricity as sole primary energy source):
  - > 1200 MW electric power
  - ≈ 10 TWh_{el} annually (about 7 % of annual Norwegian power generation)
~70% efficiency for \( \text{H}_2 \) production, \( \text{CO}_2 \) capture and \( \text{H}_2 \) liquefaction

<table>
<thead>
<tr>
<th>Input/Output</th>
<th>MW(_{\text{LHV}})</th>
<th>MW(_{\text{HHV}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas input</td>
<td>810.9</td>
<td>891.7</td>
</tr>
<tr>
<td>Hydrogen LH(_2) product output</td>
<td>694.4</td>
<td>821.2</td>
</tr>
<tr>
<td>Net power requirement</td>
<td></td>
<td>245.2</td>
</tr>
</tbody>
</table>

**Plant Efficiency** (1\textsuperscript{st} law efficiency)

<table>
<thead>
<tr>
<th></th>
<th>LHV basis</th>
<th>HHV basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stand-alone for the NG-based system</td>
<td>66.9 %</td>
<td>72.8 %</td>
</tr>
<tr>
<td>Stand-alone for the electrolyser-based system</td>
<td>57.1 %</td>
<td>67.5 %</td>
</tr>
<tr>
<td>Overall for the 450 + 50 t/d plant</td>
<td>65.8 %</td>
<td>72.2 %</td>
</tr>
</tbody>
</table>

Including > 93 % \( \text{CO}_2 \) capture ratio
Hydrogen produced from natural gas with CCS will have lower GHG emissions than hydrogen from electricity in the EU grid for decades

- Comparison of greenhouse gas emissions related to production of hydrogen from
  - European grid electricity via electrolysers
  - Natural gas with carbon capture

- Hydrogen production from natural gas using autothermal reformers with 93% (2016) to 96% (2030 - 2050) CO$_2$ capture ratio

- European grid electricity mix shown in the pie-chart – forecasts based upon the IRENA REmap case for 2030 and the decarbonised scenarios from "A Clean Planet for All" for 2050

- Without deep decarbonization of the European power generation, emissions from production of hydrogen from dedicated renewably based electricity must account for potentially reduced emission reductions of the power sector
The potential for reducing Europe's greenhouse gas emission by use of clean hydrogen is more than 800 Mt CO₂/year in 2050 (19% of current GHG emissions)

- Estimated upper bounds for annual emission reductions in Europe due to the use of hydrogen to replace fossil fuels
- Hydrogen consumption estimated from predictions for final energy consumption in 2050
- Total potential: 813 Mt CO₂ (2016 emissions: 4300 Mt CO₂)
Almost 20% of current European CO$_2$ emissions can be abated by clean hydrogen in 2050.

- **Power; 29 Mt abated**
- **Industry; 207 Mt abated**
- **Transport; 276 Mt abated**
- **Residential and commercial; 301 Mt abated**
Technology for a better society