HyStORM - sustainable, decentralized hydrogen generation and storage

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http://ceet.tugraz.at/fuelcells
Outline

- **Introduction**
  *From the idea to implementation*

- High-purity hydrogen from renewables
  *Advances in a 10 kW lab demonstration system*

- 100 bar high-pressure hydrogen
  *Pre-pressurized $H_2$ release*

- Conclusion and Outlook
Introduction
RESC process in the context of hydrogen production pathways
Introduction

RESC process in the context of hydrogen production pathways

**RESC**
Reformer Steam Iron Cycle

\[
\begin{align*}
3 \text{Fe} + 4 \text{H}_2\text{O} & \rightleftharpoons \text{Fe}_3\text{O}_4 + 4 \text{H}_2 \\
\text{Fe}_3\text{O}_4 + 4 \text{CO} / \text{H}_2 & \rightleftharpoons 3 \text{Fe} + 4 \text{CO}_2 / \text{H}_2
\end{align*}
\]

Pure Hydrogen

WATER
BIOGAS
FOSSILS
LEAN GAS
GASIFIED
BIOMASS

**STEP 1**
REDUCTION

**STEP 2**
STEAM OXIDATION

HYDROGEN

**Conclusion**
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Advances in 10 kW lab system
Lab demonstration system

High-purity Hydrogen from Biogas with a Combined Reformer and Fixed-Bed Chemical Looping System

Introduction
High-purity $\text{H}_2$
CO$_2$ Sequestration
Pressurized $\text{H}_2$
Conclusion

Simplified process scheme and lab system

Synthetic Biogas
Reformer
Chemical Looping
Electric furnace
Gas analysis
Condenser
Product gas out
Steam

Synthetic Biogas
Steam
Condenser
Gas analysis
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Electric furnace
Product gas out
Advances in a 10 kW lab system

Hydrogen purity

- Low S/C ratio for optimized performance
- MDR of biogenic feedstocks induces elevated carbon monoxide content
- Avoidance of low temperature areas in the system is crucial for hydrogen purity

<table>
<thead>
<tr>
<th>Process</th>
<th>Reaction</th>
<th>ΔH&lt;sub&gt;R,298&lt;/sub&gt; (kJ mol&lt;sup&gt;-1&lt;/sup&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boudouard</td>
<td>2 CO → C + CO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>75</td>
</tr>
<tr>
<td>MDR</td>
<td>CH&lt;sub&gt;4&lt;/sub&gt; + CO&lt;sub&gt;2&lt;/sub&gt; → 2 CO + 2 H&lt;sub&gt;2&lt;/sub&gt;</td>
<td>206</td>
</tr>
<tr>
<td>SMR</td>
<td>CH&lt;sub&gt;4&lt;/sub&gt; + H&lt;sub&gt;2&lt;/sub&gt;O → CO + 3 H&lt;sub&gt;2&lt;/sub&gt;</td>
<td>247</td>
</tr>
</tbody>
</table>
Advances in a 10 kW lab system

Hydrogen purity

- MDR ratio <28%: Excellent hydrogen purity (>99.998%)
- MDR ratio ~76%: Good hydrogen purity (>99.996%), unsteady behavior of impurities
- MDR ratio 100%: Significant carbon deposition and lower purity (<99.98%)

<table>
<thead>
<tr>
<th>Operating point</th>
<th>Biogas CH₄:CO₂</th>
<th>O/R ratio</th>
<th>MDR ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>75:25</td>
<td>1.2</td>
<td>28%</td>
</tr>
<tr>
<td>2</td>
<td>45:55</td>
<td>1.2</td>
<td>100%</td>
</tr>
<tr>
<td>3</td>
<td>75:25</td>
<td>1.6</td>
<td>21%</td>
</tr>
<tr>
<td>4</td>
<td>45:55</td>
<td>1.6</td>
<td>76%</td>
</tr>
</tbody>
</table>

Hydrogen product gas stream in oxidation phase

Graphics adapted from: Bock et al., 2019, RSC Advances, DOI:10.1039/C9RA03123E (CC BY 3.0)
Advances in a 10 kW lab system
Hydrogen storage and long-term experience

- Up to 60% feedstock utilization for high-purity H₂ - 99.999%
- 1000 hours time-on-stream, over one year of discontinuous operation
- Loss-free energy storage equal to 1000 bar PH₂
- On-time hydrogen generation e.g. for decentralized systems

Excerpt of long-term test series

Introduction
High-purity H₂
CO₂ Sequestration
Pressurized H₂
Conclusion

Graphics adapted from: Bock et al., 2019, RSC Advances, DOI:10.1039/C9RA03123E (CC BY 3.0)
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- **Conclusion and Outlook**
100 bar high-pressure hydrogen

Pre-pressurized $H_2$ release

- System-integrated 100 bar pre-pressurized release demonstrated in lab system by water feed liquid compression

- Significant energy savings for 1000 bar allocation

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100 bar high-pressure hydrogen
Pre-pressurized $H_2$ release

Hydrogen release after full reduction

Hydrogen release after reduction with $CO_2$ sequestration

Zacharias et al., 2019, Int. J Hydrogen Energy, DOI:10.1016/j.ijhydene.2019.01.257 (CC BY-NC-ND 4.0)
Conclusion

- **Hydrogen from decentralized available resources** for low-temperature fuel cells
- **High product gas purity (99.999%)**
- **Feedstock utilization up to 60%**
- **Zero- or negative carbon dioxide emissions** with CCS/CCU
- **Loss-free energy storage**
- **On-time hydrogen generation**

- **Pressurized release at 100 bar** demonstrated
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