A future energy chain based on liquefied hydrogen

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Outline

- Introduction to the role of liquefaction in an energy chain with hydrogen as energy carrier
- Comparison of existing and proposed conceptual hydrogen liquefiers
- Selection of a high-efficiency case for the following tasks:
  - Replacement of original pre-cooling of hydrogen to 75 K with a new pre-cooling cycle based on mixed refrigerant (MR) technology
  - Investigate the consequences of this modification with respect to power consumption and process efficiency
- LH$_2$ in relation to LNG
- Conclusions and further work
Previous Shell study on hydrogen well-to-wheel \(^1\)

- Early-phase scenario: reforming of methane, CO\(_2\) capture and bulk transportation of hydrogen from production site to retail site
- Liquid hydrogen (LH\(_2\)) vs. compressed gaseous hydrogen (CGH\(_2\))

\[\text{Assumed specific liquefaction power for LH}_2:\ 10 \text{ kWh/kg}_{\text{LH}_2}\]
Average distribution distance: 75 km
Production volume: 100 tonnes/day
Number of retail sites: 100
LH\(_2\) transport capacity: 3500 kg/truck
CGH\(_2\) transport capacity: 350 kg/truck
Advantages of LH₂

- Flexibility – With close to equal overall cost, LH₂-based distribution enables delivery of hydrogen in any form with low energy consumption at retail-side filling stations.
- CGH₂ does not offer this flexibility without on-site refrigeration.
# Transition from current LH$_2$ production

<table>
<thead>
<tr>
<th></th>
<th>Existing liquefiers</th>
<th>Envisioned future liquefiers</th>
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<tbody>
<tr>
<td><strong>Market</strong></td>
<td>LH$_2$ for specific industrial purposes</td>
<td>LH$_2$ as an energy commodity</td>
</tr>
<tr>
<td><strong>Plant capacity</strong></td>
<td>4.4 tonnes/day (Ingolstadt, 1992)$^1$</td>
<td>Significant scale-up in capacity (50–100 tonnes/day or more)</td>
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<td></td>
<td>5.0 tonnes/day (Leuna, 2007)$^2$</td>
<td></td>
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<tr>
<td><strong>Specific liquefaction power consumption</strong></td>
<td>13.6 kWh/kg (Ingolstadt)$^1$</td>
<td>Considerably lower due to higher emphasis on energy efficiency, scaling-up advantages and shifted cost structure</td>
</tr>
<tr>
<td></td>
<td>11.9 kWh/kg (Leuna)$^2$</td>
<td></td>
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<tr>
<td></td>
<td>(10 kWh/kg used in Shell study)</td>
<td></td>
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<tr>
<td><strong>Operation</strong></td>
<td>Flexible operation (Leuna: 40–100% load range)</td>
<td>Large base-load plants with high efficiency at full load</td>
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</tbody>
</table>


Efficiency of hydrogen liquefiers

![Graph showing specific power vs. overall exergy efficiency for existing plants and recently proposed large-scale concepts.](image)

Efficiency of hydrogen liquefiers

![Graph showing overall exergy efficiency and specific power for different feed pressures.]

Efficiency of hydrogen liquefiers

Comparison of efficiency based on equal boundary conditions

Efficiency of hydrogen liquefiers

![Graph showing specific power vs. overall exergy efficiency for different feed pressures.]

Selecting a reference case for our work

- The concept by Prof. Quack\(^1\) (2001) is the most efficient concept published – we have therefore based our work on this concept and using it as reference process.

- Changed assumptions of the reference process to be more conservative than in original configuration:
  - For pre-cooling to 220 K, the original 3-stage propane cycle is replaced with 2-stage propane + single-stage ethane refrigeration cycles.
  - Assumed 21 bar feed pressure instead of 1 bar.
  - Inter-cooler temperature in compressor trains: 310 K.
  - Implemented pressure drop in all heat exchangers and inter-coolers.
  - Minimum temperature approach (MTA) in heat exchangers:
    - Above 235 K: MTA = 3 K
    - Below 235 K: MTA = 2 K

- Liquefaction capacity: 86 tonnes/day (~ 1 kg/s).
- Resulting exergy efficiency: 45.7%.

Implementing mixed refrigerant pre-cooling in the reference case

Utilities in the different temperature intervals

- Pre-compression to 80 bar
- Expansion to 1 bar
- 2-stage propane cycle
- 1-stage ethane cycle
- Reversed Helium/Neon Brayton cycle with internal recuperation
- Mixed refrigerant pre-cooling cycle
- Reversed Helium/Neon Brayton cycle with internal recuperation
Liquefaction process modified with MR pre-cooling
Power figures and overall results

<table>
<thead>
<tr>
<th></th>
<th>Reference case</th>
<th>Modified MR case with J-T expansions</th>
<th>Modified MR case with liquid expanders</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Electric power [MW]</td>
<td>Electric power [MW]</td>
<td>Electric power [MW]</td>
</tr>
<tr>
<td>He/Ne compression</td>
<td>23,139</td>
<td>14,867</td>
<td>14,869</td>
</tr>
<tr>
<td>H2 feed compression</td>
<td>2,401</td>
<td>2,401</td>
<td>2,401</td>
</tr>
<tr>
<td>Propane-ethane/MR compression</td>
<td>0,732</td>
<td>7,392</td>
<td>6,330</td>
</tr>
<tr>
<td>H2 flash-gas compression</td>
<td>0,043</td>
<td>0,043</td>
<td>0,043</td>
</tr>
<tr>
<td>Total compression power</td>
<td>26,315</td>
<td>24,703</td>
<td>23,643</td>
</tr>
<tr>
<td>He/Ne expansion</td>
<td>3,443</td>
<td>1,271</td>
<td>1,271</td>
</tr>
<tr>
<td>H2 liquid expansion</td>
<td>0,086</td>
<td>0,086</td>
<td>0,086</td>
</tr>
<tr>
<td>MR expansion</td>
<td>0</td>
<td>0</td>
<td>0,085</td>
</tr>
<tr>
<td>Total expansion power</td>
<td>3,529</td>
<td>1,357</td>
<td>1,442</td>
</tr>
<tr>
<td>Net power consumption</td>
<td>22,786</td>
<td>23,346</td>
<td>22,201</td>
</tr>
<tr>
<td>Specific power consumption [kWh/kg]</td>
<td>6,33</td>
<td>6,49</td>
<td>6,17</td>
</tr>
<tr>
<td>Exergy efficiency</td>
<td>45,7 %</td>
<td>44,6 %</td>
<td>46,9 %</td>
</tr>
</tbody>
</table>

- Replacement of J-T valves with rotating liquid expanders (85% isentropic efficiency):
  - Reduces MR HP/LP ratio from 22.4 to 12.4
  - Reduces MR compression power by 17%
LH₂ related to LNG

- Lower heating value:
  - LNG: ~13.6 kWh/kg (~49 MJ/kg)
  - LH₂: 33.4 kWh/kg (120 MJ/kg)

- Reversible liquefaction power (specific):
  - LNG: 0.11 kWh/kg (Snøhvit gas, Hammerfest conditions)
  - LH₂: 2.89 kWh/kg (21 bar feed pressure, 300 K ambient temperature)

- The Snøhvit LNG plant:
  - Specific design power consumption: 0.23 kWh/kg¹
  - Exergy efficiency: ~48%

- The best-performance LH2 process with MR pre-cooling:
  - Specific design power consumption: 6.17 kWh/kg
  - Exergy efficiency: ~47%

**LH₂ related to LNG**

- **Existing H₂ liquefiers in Germany**
- **LH₂ in this work with MR pre-cooling**
- **Snøhvit LNG**

The graph shows the specific power consumption relative to LHV as a function of the exergy efficiency of liquefaction.
Conclusion

- The LH₂ processes employing MR pre-cooling show a specific power consumption of 6.17–6.49 kWh/kg and exergy efficiency of 44.6–46.9%
- 40–50% reduction of power consumption, down from 12 to 6–7 kWh/kg, will represent a radical improvement within large-scale hydrogen liquefaction and contribute to further enhancement of the competitiveness of LH₂ as energy carrier in an hydrogen-based energy chain
- As for LNG, MR pre-cooling may play an important role in the efforts towards efficient large-scale liquefaction processes
- High exergy efficiency is desired and may be obtainable for large-scale liquefiers with energy optimisation, extensive process integration and high-efficiency compressors and expanders
Further work: continuation project proposal

- **Theoretical studies (SP 3)**
  - MR pre-cooling
  - MR freeze-out
  - Ortho-para conversion

- **Experimental development (SP 4)**
  - MR pre-cooling
  - MR freeze-out
  - Ortho-para conversion

- **Large-scale liquefaction plants (SP 1)**
  - Modelling and simulation
  - Components and system elements verification
  - Evaluation of interaction between liquefaction and other utilities and uses

- **From well to end-user (SP 2)**
  - Case development
  - Modelling and simulation of complete chains for the given cases

- **Education and dissemination (SP 5)**

- **Management (SP 6)**
Acknowledgements

Financial support

Scientific support