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
- LH₂ in relation to LNG
- Conclusions and further work
Previous Shell study on hydrogen well-to-wheel

- 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$_2$)

<table>
<thead>
<tr>
<th>H$_2$ cost ($/kg)</th>
<th>Retail-site operations</th>
<th>Distribution</th>
<th>Manufacturing</th>
</tr>
</thead>
<tbody>
<tr>
<td>central gaseous</td>
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<tr>
<td>central liquid</td>
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<td>central liquid</td>
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<tr>
<td>on-site reforming</td>
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<td>on-site electrolysis</td>
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</tbody>
</table>

Assumed specific liquefaction power for LH$_2$: 10 kWh/kg$_{LH2}$
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

1Kramer G.J., Huijsmans J.P.P. and Austgen D.M. Clean and green hydrogen. 16th World hydrogen energy conference, 2006
Advantages of LH$_2$

- **Flexibility** – With close to equal overall cost, LH$_2$-based distribution enables delivery of hydrogen in any form with low energy consumption at retail-side filling stations.
- **CGH$_2$** 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>
</tr>
</thead>
<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>
</tr>
<tr>
<td></td>
<td>5.0 tonnes/day (Leuna, 2007)$^2$</td>
<td></td>
</tr>
<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>
</tr>
<tr>
<td></td>
<td>(10 kWh/kg used in Shell study)</td>
<td></td>
</tr>
<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>
</tr>
</tbody>
</table>


Efficiency of hydrogen liquefiers


Berstad D., Stang J. and Nekså P.
Efficiency of hydrogen liquefiers

Efficiency of hydrogen liquefiers

Comparison of efficiency based on equal boundary conditions

Efficiency of hydrogen liquefiers

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

- Process (H₂)
  - Pre-compression to 80 bar
  - Expansion to 1 bar

Utilities

- Original reference process
- Modified process with mixed refrigerant (MR)

310 K 235 K 220 K 75 K 26 K 20 K

- 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

LH₂
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><strong>Total compression power</strong></td>
<td><strong>26,315</strong></td>
<td><strong>24,703</strong></td>
<td><strong>23,643</strong></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</td>
</tr>
<tr>
<td><strong>Total expansion power</strong></td>
<td><strong>3,529</strong></td>
<td><strong>1,357</strong></td>
<td><strong>1,442</strong></td>
</tr>
<tr>
<td><strong>Net power consumption</strong></td>
<td><strong>22,786</strong></td>
<td><strong>23,346</strong></td>
<td><strong>22,201</strong></td>
</tr>
<tr>
<td><strong>Specific power consumption [kWh/kg]</strong></td>
<td><strong>6,33</strong></td>
<td><strong>6,49</strong></td>
<td><strong>6,17</strong></td>
</tr>
<tr>
<td><strong>Exergy efficiency</strong></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%
LH$_2$ related to LNG

- Lower heating value:
  - LNG: ~13.6 kWh/kg (~49 MJ/kg)
  - LH$_2$: 33.4 kWh/kg (120 MJ/kg)

- Reversible liquefaction power (specific):
  - LNG: 0.11 kWh/kg (Snøhvit gas, Hammerfest conditions)
  - LH$_2$: 2.89 kWh/kg (21 bar feed pressure, 300 K ambient temperature)

- The Snøhvit LNG plant:
  - Specific design power consumption: 0.23 kWh/kg\(^1\)
  - 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

Exergy efficiency of liquefaction

Specific power consumption relative to LHV

Existing H₂ liquefiers in Germany

LH₂ in this work with MR pre-cooling

Snøhvit LNG
Conclusion

- The LH$_2$ 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 LH$_2$ 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