Large-Scale Hydrogen Production and Liquefaction for Regional and Global Export

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International Hydrogen and Fuel Cells Conference, Trondheim, 14–15 May 2018
Motivation for hydrogen export from Norway

• Rich energy resources, especially from natural gas, oil and hydro power
• The potential for wind power generation is large, particularly in remote areas
• Benefits from liquid hydrogen export:
  o **De-bottlenecking**: Potentially reducing the need for extensive
    • power transmission capacity upgrades in remote areas
    • gas transport pipelines in remote areas (Barents Sea)
  o **Decarbonisation** of fossil energy resources with CCS
    • Storage already demonstrated on the Norwegian shelf
    • Potential for synergies and cost splitting with other CCS projects
  o **Strategic diversification** of customer base for Norwegian energy

Wind power capacity installed and under construction
Norway: Renewable power and fossil energy
Examples of **scale** of production

**Hydrogen fuelling stations**

- **"Small"**
  - 0.2–1 ton/d
  - (≈ 0.4–2 MW)

- **"Medium"**
  - 30 ton/d
  - (≈ 50 MW)

- **"Large"**
  - 500 ton/d
  - (> 1000 MW)

**Domestic use in industry (Tizir, Tyssedal)**

- Production, liquefaction of LH₂ for long-distance bulk transport

**Scale of the Hyper project**

- Source: Kawasaki Heavy Industries

- $x \times 500–2500$
In perspective: 500 ton liquid hydrogen per day

- Energy flux in the hydrogen product stream:
  - $5.8 \text{ kg/s} \cdot 142 \text{ MJ}_{\text{HHV}}/\text{kg} \approx 820 \text{ MW}_{\text{HHV}}$
- About 7 200 m$^3$ liquid hydrogen per day
- Equivalent to one 160 000 m$^3$ ship load about every 3 weeks
- Corresponds to about 7 TWh per year of hydrogen energy output
- Use of only electricity as energy source would require > 1200 MW power, and ≈ 10 TWh annually (about 7 % of annual domestic power generation)
- Use of natural gas would be < 1 % of annual domestic production

Source: Kawasaki Heavy Industries
Scale of liquid hydrogen storage

Prospective LH₂ carrier
4 x 40 000 m³
11 000 t

Existing

JAXA, Japan
540 m³
38 t

NASA, USA
3 800 m³
270 t

LH₂ truck
< 50 m³
< 3.5 t

50 000 m³
3 500 t

40 000 m³
2 800 t

≈ 45 m
≈ 12 m
≈ 20 m

Image source: Kawasaki Heavy Industries, NASA
Purpose of hydrogen liquefaction

- Enabling high-density storage and transport at low pressure
- Transport and storage economics analogous to LNG vs. CNG vs. pipeline
The Hyper concept (www.sintef.no/hyper)

Primary energy sources
- Natural gas
  → Hydrogen + CO\textsubscript{2}
  → Heat + power
- Renewable power
  → Hydrogen (+ O\textsubscript{2})
  → Auxiliary processes

Main research areas in Hyper
- Process design and modelling of hydrogen production and liquefaction systems
- Modelling and simulation of key process units
- Modelling of electrolysis-based hydrogen production in constrained grids
Example: Advanced LH₂ production plant layout

- Natural gas feedstock
- Pre-reformer
- Auto-thermal reformer
- High-temperature water-gas shift
- Low-temperature water-gas shift
- Shifted syngas: H₂, H₂O, CO₂, CO, ...
- Pd membrane
- Tail gas to combustor
- Exhaust
- Steam generation
- Steam turbines
- Tail gas combustor
- Steam
- Steam
- H₂ compression
- CH₂ buffer storage
- H₂ Liquefiers
- LH₂ storage
- Alkaline water electrolysis
- Waste O₂
- Water
- O₂ compression
- Cryogenic air separation
- Physical CO₂ separation
- Retentate: CO₂, H₂O, H₂, CO, ...
- Boil-off H₂
- 50 t/d
- 450 t/d
- 500 t/d
- H₂
Large-scale, high-efficiency H₂ liquefaction

Liquefaction power vs. liquefier exergy efficiency

State of the art (5–10 t/d blocks)

"Hyper liquefier" (100 t/d blocks)

Long-term potential

20 bar feed pressure


Example of overall results, 500 ton LH\textsubscript{2} per day

450 ton/d from reforming + 50 ton/d from water electrolysis

<table>
<thead>
<tr>
<th></th>
<th>MW\textsubscript{LHV}</th>
<th>MW\textsubscript{HHV}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas input</td>
<td>811</td>
<td>892</td>
</tr>
<tr>
<td>Net power requirement</td>
<td>245 MW\textsubscript{el}</td>
<td></td>
</tr>
<tr>
<td>Hydrogen LH\textsubscript{2} product output</td>
<td>694</td>
<td>821</td>
</tr>
</tbody>
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"1\textsuperscript{st}-Law" efficiency

<table>
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<tr>
<th></th>
<th>LHV basis</th>
<th>HHV basis</th>
</tr>
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<tbody>
<tr>
<td>Overall for the 450 + 50 t/d plant</td>
<td>65.8 %</td>
<td>72.2 %</td>
</tr>
<tr>
<td>With oxygen integration from electrolysers</td>
<td>66.0 %</td>
<td>72.4 %</td>
</tr>
</tbody>
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Including CO\textsubscript{2} capture at CO\textsubscript{2} compression for pipeline transport, at 93.4 % CO\textsubscript{2} capture ratio
Oxygen supply to ATR from electrolyzers

Oxygen self-sufficiency can be achieved when electrolyser hydrogen production capacity exceeds about 1/3 of total hydrogen output.
"Blue hydrogen" vs. "Green hydrogen"

Post-commissioning CO₂-eq. emissions:
CO₂-intensity of hydrogen from electrolysis vs. from autothermal reforming with 93.4 % CO₂ capture intersect at approximately 16 gCO₂/kWh_{el}

"y = A\chi"

"y = B\chi + C"

CO₂ intensity of H₂ product [kg/MWh_{HHV}]

"y"

CO₂ intensity of electricity [kg/MWh_{el}]

16 kg/MWh_{el} Norway average (2016)

Water electrolysis + Liquefaction

Natural gas reforming with 93.4 % CO₂ capture
Up-/midstream GHG emissions included + Liquefaction

"x"
Acknowledgements

This publication is based on results from the research project Hyper, performed under the ENERGIX programme. The authors acknowledge the following parties for financial support: Statoil, Shell, Kawasaki Heavy Industries, Linde Kryotechnik, Mitsubishi Corporation, Nel Hydrogen and the Research Council of Norway (255107/E20).
Teknologi for et bedre samfunn