Latest Global Trend in Liquid Hydrogen Production

HYPER Closing Seminar

Lutz Decker
Brussels, December 10, 2019

Making our world more productive
Agenda

1. The Rise of Liquid Hydrogen
2. The Economy of Scale
3. A Roadmap to Clean Energy
4. Recent Initiatives asking for Larger H₂ Capacities
5. Linde’s Hydrogen Value Chain for H₂ Mobility
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The Rise of Liquid Hydrogen
From Rocket Fuel to $H_2$ Mobility

**Rocket Fuel**
- **Driver**: energy density
- **Demand**: stagnating
- **Plant sizes**: up to 20+ tpd

**Conventional e.g. Semiconductor Industry**
- **Driver**: purity, distribution
- **Demand**: slight increase
- **Plant sizes**: up to 5 tpd

**Clean Energy and $H_2$ Mobility**
- **Driver**: distribution
- **Demand**: potential boost
- **Plant sizes**: 20 to 50+ tpd

Latest Global Trend in Liquid Hydrogen Production, L. Decker, HYPER, Brussels
The Rise of Liquid Hydrogen
LH₂ Liquefaction Capacities until 1980

90 t/day
USA

1.3 t/day
Japan
The Rise of Liquid Hydrogen
LH₂ Liquefaction Capacities until 1990

- USA: 128 t/day
- Canada: 51 t/day
- Europe: 15 t/day
- South America: 2.3 t/day
- Japan: 4.5 t/day

Latest Global Trend in Liquid Hydrogen Production, L. Decker, HYPER, Brussels
The Rise of Liquid Hydrogen
LH₂ Liquefaction Capacities until 2000

- USA: 208 t/day
- Canada: 51 t/day
- South America: 2.3 t/day
- Europe: 20 t/day
- Asia (excl. Japan): 0.5 t/day
- Japan: 4.5 t/day

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The Rise of Liquid Hydrogen

LH₂ Liquefaction Capacities until 2010

- 208 t/day, USA
- 51 t/day, Canada
- 2.3 t/day, South America
- 20 t/day, Europe
- 2.5 t/day, Asia (excl. Japan)
- 21 t/day, Japan
The Rise of Liquid Hydrogen
LH₂ Liquefaction Capacities today

241 t/day
USA

51 t/day
Canada

2.3 t/day
South America

20 t/day
Europe

2.5 t/day
(excl. Japan)
Asia

31 t/day
Japan
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The Economy of Scale
Limited Data on Efficiency

Published data on existing plants

<table>
<thead>
<tr>
<th>Location</th>
<th>TPD tonnes per day</th>
<th>specific energy consumption feed compression excluded</th>
<th>supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ingolstadt/D</td>
<td>4.5 (1992)</td>
<td>12.0 kWh/kg$_{LH2}$</td>
<td>Linde</td>
</tr>
<tr>
<td>Leuna/D</td>
<td>5.3 (2007)</td>
<td>10.3 kWh/kg$_{LH2}$</td>
<td>Linde</td>
</tr>
<tr>
<td>USA</td>
<td>5.4 to 32.0</td>
<td>15 to 12.5 kWh/kg$_{LH2}$[*1]</td>
<td>Praxair</td>
</tr>
</tbody>
</table>

* boundary conditions not stated
The Economy of Scale
Limited Data on Efficiency

Linde R&D

Energy demand [kWh/kg LH₂] (excluding Feed Compression) (incl. LIN production)

- 9.6 \( n_{ex}=28\% \)
- 7.4
- 6.4 \( n_{ex}=45\% \)

as built**
internal
participation
internal
5 TPD
50 TPD
50 TPD
50 to 150 TPD
(2011)
(2010)
(2013)
(2016)

** improved design

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The Economy of Scale
Specific Liquefaction Cost

Total expenditure (TOTEX) = capital expenditure (CAPEX) + operational expenditure (OPEX)

General boundary conditions
- turnkey w/o land
- 20 years depreciation
- 0.05 €/kWh
- feed compression excluded

Medium term future
- within 5 years from project start
- modification of proven technology
The Economy of Scale
Optimum Distribution Concept – Yang & Ogden

The Economy of Scale
Optimum Distribution Concept

- efficiency rising with capacity
- more realistic prices on liquid distribution

Compressed Gas Truck
Liquid Truck
Pipeline

Transport Distance →

only indicative extrapolation
The Economy of Scale
Optimum Distribution Concept

large H₂ capacities amplify advantage of liquid distribution!
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A Roadmap to Clean Energy
Starting with 1% Market Share of Mobility Fuel

Mobility fuel market: 6.6 billion USD/day
USA / EU / Japan / ROK / China (2014)

1% of fuel market: H₂: 24 billion USD/year
USA / EU / Japan / ROK / China

Assumptions: diesel & oil: ~ 50% of oil
Fuel: gasoline + diesel & oil
4 USD/gal average

Assumption: 1% of fuel equivalent price

Replacing 1% of today’s fuel consumption by hydrogen is a big deal.
A Roadmap to Clean Energy
Back-to-Base Fleets as Market Access

Key numbers on H₂ consumption

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>H₂ cons. rate [tpd]</th>
<th>Fuel type</th>
<th>Units served by liquefier</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>H₂</td>
<td>5 tpd</td>
</tr>
<tr>
<td>car (California)</td>
<td>0.0008</td>
<td>compressed gas</td>
<td>6 000</td>
</tr>
<tr>
<td>bus / truck</td>
<td>0.03</td>
<td>compressed gas</td>
<td>167</td>
</tr>
<tr>
<td>train</td>
<td>0.25</td>
<td>compressed gas</td>
<td>20</td>
</tr>
<tr>
<td>Inland navigation, ferries</td>
<td>0.4-1.5</td>
<td>liquid</td>
<td>4</td>
</tr>
<tr>
<td>coastal ship</td>
<td>2</td>
<td>liquid</td>
<td>2.5</td>
</tr>
<tr>
<td>cruiser ship</td>
<td>10</td>
<td>liquid</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Back-to-base fleets reduce initial investment in infrastructure.
Few large scale consumers trigger the price level for small scale!
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Recent Initiatives asking for Larger H₂ Capacities
Ferries in Norway and France / Trucks in Switzerland

13 May 2019

FLAGSHIPS project to deploy two hydrogen vessels

The European innovation project FLAGSHIPS has been awarded 5 Million Euros from the EU to support deploying two commercially operated zero-emission hydrogen fuel cell vessels in France and Norway...


19 September 2018

Hyundai and H₂ Energy to launch world’s first fleet of Fuel Cell Truck

Hyundai Motor, in cooperation with H₂ Energy, to provide 1,000 fuel cell electric trucks to Swiss commercial vehicle market, beginning 2019 through to 2023...


1,600 FC trucks until 2025
Recent Initiatives asking for Larger H₂ Capacities
Trains in Germany

16 Sep 2018
World premiere: Alstom’s hydrogen trains enter passenger service in Lower Saxony
It was a world premiere being celebrated ...
... 2021, when Alstom will deliver a further 14 Coradia iLint trains ...

21 May 2019
RMV’s subsidiary fahma orders the world’s largest fleet of fuel cell trains from Alstom
• A contract worth around €500 million
• ...
RMV’s subsidiary fahma issued a tender for 27 fuel cell trains throughout Europe...
Recent Initiatives asking for Larger H₂ Capacities
LH₂ Liquefaction Capacities today

- USA: 241 t/day
- Canada: 2.3 t/day
- South America: 20 t/day
- Europe: 2.5 t/day
- Asia (excl. Japan): 31 t/day
- Japan: 31 t/day

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Recent Initiatives asking for Larger H₂ Capacities
LH₂ Liquefaction Capacities planned for 2021

- USA: 241 t/day
- Canada: 51 t/day
- South America: 2.3 t/day
- Europe: 20 t/day
- Asia (excl. Japan): 31 t/day
- Japan: 5.3 t/day
- Australia: demo

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A Roadmap to Clean Energy
Starting with 1% Market Share of Mobility Fuel

Market share for H₂ in mobility
176,000 t/day

Market share for LH₂ in H₂ mobility
17,600 t/day

Latest Global Trend in Liquid Hydrogen Production, L. Decker, HYPER, Brussels
1% market share for H$_2$ in mobility fuel
176,000 t/day

10% market share for LH$_2$ in H$_2$ mobility
17,600 t/day
A Roadmap to Clean Energy
Starting with 1% Market Share of Mobility Fuel

1% market share for H₂ in mobility fuel
176,000 t/day

10% market share for LH₂ in H₂ mobility
17,600 t/day

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Linde’s Hydrogen Value Chain for H₂ Mobility
Supply and Consumer

H₂ Consumers [kg/day]
- H₂ Bus: 30 kg/d
- H₂ Car: 0.8 kg/d
- H₂ Train: 250 kg/d

H₂ Supply [kg/day]
- H₂ Pipelines: 2'500 kg/d
- H₂ liquefaction plant: 3'500 kg/d
- CGH₂ trailer: 900 kg CGH₂
- Off-grid power supply: 1-10 tpd

Other processes include:
- Steam reforming for H₂ production
- H₂ refuelling
Linde’s Hydrogen Value Chain for H₂ Mobility
Linde Covers the Full Value Chain!

Production
- Conventional (e.g. SMR)
- Renewable (e.g. electrolysis)
- Onsite electrolysis

Distribution & Storage
- LH₂ liquid hydrogen
- CGH₂ compressed gaseous hydrogen
- Liquefaction

H₂ Fueling Stations
- Cryopump
- Ionic compressor
- Boil-off mgmt. system
- Dispenser

Infrastructure & Vehicles
- Out of one hand
  Reliable operations of H₂ supply and fuelling equipment to a range of mobility applications
Linde’s hydrogen liquefaction
The core competence - technology

Innovative technology of unique dynamic gas bearing turbine

Proven track record:
The majority of the world’s installed hydrogen liquefaction plants have been built by Linde

Inhouse produced PFHX for highest quality and long lifetime

Lowest total cost of ownership concepts for different ranges

Small  <1 tpd  (Hé cycle)
Medium  ~5 tpd  (H₂ cycle)
Large  >30 tpd  (H₂ cycle)

Complete inhouse cold box assembly to ensure high quality and full control of delivery time

Full EPC capability
LH2 solution provider

Ready for the future
Concepts with record efficiencies for plants up to 100 tpd available
Linde’s hydrogen liquefaction
Proven track of hydrogen liquefaction projects

On-stream until 1999

<table>
<thead>
<tr>
<th>Location</th>
<th>Capacity [tpd]</th>
<th>On-stream</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>20</td>
<td>1962</td>
</tr>
<tr>
<td>USA</td>
<td>16</td>
<td>1981</td>
</tr>
<tr>
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<td>16</td>
<td>1988</td>
</tr>
<tr>
<td>Canada</td>
<td>16</td>
<td>1989</td>
</tr>
<tr>
<td>Germany</td>
<td>5</td>
<td>1992 (†)</td>
</tr>
<tr>
<td>USA</td>
<td>30</td>
<td>1995</td>
</tr>
<tr>
<td>China</td>
<td>&lt;1</td>
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</tr>
<tr>
<td>USA</td>
<td>30</td>
<td>1997</td>
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</table>

On-stream from 2000 on

<table>
<thead>
<tr>
<th>Location</th>
<th>Capacity [tpd]</th>
<th>On-stream</th>
</tr>
</thead>
<tbody>
<tr>
<td>Japan</td>
<td>&lt;1</td>
<td>2003</td>
</tr>
<tr>
<td>India</td>
<td>1</td>
<td>2005</td>
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<td>Japan</td>
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<td>2021</td>
</tr>
<tr>
<td>USA</td>
<td>30</td>
<td>2021</td>
</tr>
</tbody>
</table>

Note: Due to non-disclosure agreements, the reference list is not complete.
Summary

– For the supply of hydrogen mobility programs, a significant increase in hydrogen production is expected, e.g. based growing demand for fuel cells
– Gaseous supply is often more economical at small scale <200 kg/day and local consumption
– Large volumes of hydrogen, in particular distribution on long distance and high power consumption in clean mobility is preferably done with liquid hydrogen
– The transition to clean mobility asks for huge production capacities of hydrogen
– The technology of hydrogen liquefaction is well established and improves with economy of scale

Linde’s capabilities:
– Linde has broad experience for gaseous as well as liquid hydrogen.

(commuting train Alstom) driven from hydrogen generated by electrolysis coming from wind power.
Making our world more productive

Thank you for your attention

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