LIQUID ORGANIC HYDROGEN CARRIERS – A TECHNOLOGY TO OVERCOME COMMON RISKS OF HYDROGEN STORAGE

ICHS2021 – Hydrogen storage – ID5

21st September 2021

Dr. Berthold Melcher
Agenda

- LOHC technology and its market
- Chemistry, physical and eco toxic properties
- Projects, risks and scale-up
- Outlook on marine systems
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Hydrogenious LOHC Technologies GmbH
Established in 2013, we are a global technology leader for Liquid Organic Hydrogen Carrier today

Investors

Hydrogenious is well-known worldwide and considered a pioneer in its field

Hydrogenious has a strong position in IP and patent protection world-wide.

Technology Cooperation Partners

Key Partners

Universität Erlangen

MAN Energy Solutions

EASTMAN
Decarbonise the world: Hydrogen demand will increase dramatically and also the demand for safe and easy transport of hydrogen

Potential global demand for hydrogen by 2050

- Total amount: 195EJ
- Total H2 demand: 1370MMT

Europe: Large scale hydrogen import will be mandatory due to limited national H2 production capacities

Prognosis of hydrogen imports for Germany by 2050

German National Hydrogen Strategy: 80% H2 imported by 2030

*in Million Metric Tons (MMT)
Global $\text{H}_2$ value chain and transport options needed due to cost differences in $\text{H}_2$ production – LOHC as the “Missing link”

Significant hydrogen production cost delta

<table>
<thead>
<tr>
<th>Cost ($/\text{kg} \text{H}_2)</th>
<th>Percentage Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>133%</td>
</tr>
<tr>
<td>2.0</td>
<td>250%</td>
</tr>
<tr>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>4.0</td>
<td></td>
</tr>
</tbody>
</table>

Cost differences in future hydrogen production will define sourcing strategies and global distribution. Efficient, safe and flexible handling of $\text{H}_2$ to connect supply and demand across the globe.

1) Source: IEA 2019, The future of hydrogen and *IEA 2019, Hydrogen: A renewable energy prospective (value PV costs 2050)
LOHC technology leverages the existing liquid-fuel infrastructure by transporting hydrogen in a liquid at ambient conditions.

**Hydrogen storage system**
- **H₂**
- Hydrogenation (loading LOHC)
  - Exothermic (~250°C, 25 – 50 bar)
- **StoragePLANT**
- **H₂**

**LOHC Transport System**
- Loaded LOHC
- Unloaded LOHC

**Hydrogen release system**
- **H₂**
- Dehydrogenation (unloading LOHC)
  - Endothermic (~300°C, 1 – 3 bar)
- **ReleasePLANT**

**Features**
- **Safe:** Hardly flammable liquid
- **Efficient:** High energy density
- **Flexible:** Use of existing infrastructure
Hydrogenious LOHC’ vision of a global hydrogen economy

Sustainable hydrogen sourcing
- Renewable hydrogen
  - Wind & hydro @ <3 ct/kWh
  - Solar @ <2 ct/kWh
  - >5,000 h/year production
- By-product hydrogen
  - Chlorine-alkali electrolysis
  - Others

Hydrogen distribution
- Globally Existing Infrastructure
  - Ship Transport International
    - Oil tankers & storage facilities
    - Large scale
  - Rail Transport (Inter)-national
    - Efficient rail network
    - Multi-ton transport
  - Road Transport National / regional
    - Bulk delivery
    - High flexibility

Diversified demand sites
1. Pipeline hubs International
   - Green hydrogen from international sources for pipeline distribution
2. Large industry International
   - Large-scale industrial customers with renewable heat demand
   - Green hydrogen as base chemical
3. HRS & medium scale industry Distributed national
   - High-capacity HRS
   - Hydrogen as base chemical and utility
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Hydrogenious’ LOHC technology utilizes a well known heat transfer fluid in a circular reaction scheme

(Perhydro-)Benzytoluene
- Non-explosive
- Diesel-like liquid
- Hardly flammable
- Pour point < -30 °C
- Viscosity (dynamic) 4.4 – 6.3 mPas; 20 °C
- Stored at ambient conditions
- 54 kg\(_{\text{H}_2}/\text{m}^3\)\(_{\text{LOHC}}\) and 62 kg\(_{\text{H}_2}/\text{t}\)\(_{\text{LOHC}}\)
- Commercially available product

\[ \text{H}_2 \quad \text{heat out} \quad \sim 9 \text{ kWh}_t/\text{kg}^* \]

\[ \text{H}_2 \quad \text{heat in} \quad \sim 12 \text{ kWh}_t/\text{kg}^* \]

ICH52021 - Hydrogen storage in LOHCs - ID5 - 21.09.2021

*technically usable heat – including scenario specific heat losses
BT has comparable eco toxic properties to today’s energy carriers without their flammability and acute toxicity of NH₃ and methanol

<table>
<thead>
<tr>
<th></th>
<th>DBT</th>
<th>BT</th>
<th>Toluene / MCH</th>
<th>(Marine) Diesel</th>
<th>Gasoline</th>
<th>Marine residual fuel</th>
<th>NH₃</th>
<th>Methanol</th>
<th>CGH₂ / LH₂</th>
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</thead>
<tbody>
<tr>
<td>Aquatic tox.</td>
<td>H410</td>
<td>H411</td>
<td>- / H411</td>
<td>H411</td>
<td>H411</td>
<td>H410</td>
<td>H400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carcinog./mutag.</td>
<td></td>
<td></td>
<td>H351/-</td>
<td>H350/340</td>
<td>H350/-</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Reproduct. tox.</td>
<td>H360FD</td>
<td>H360FD</td>
<td>H361</td>
<td>H361d</td>
<td>H361d</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oral toxicity</td>
<td>H304</td>
<td>H304</td>
<td>H304</td>
<td>H304</td>
<td>H304</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contact toxicity</td>
<td>H315</td>
<td>H315</td>
<td>H304</td>
<td>H304</td>
<td></td>
<td></td>
<td>H314</td>
<td>H311</td>
<td></td>
</tr>
<tr>
<td>Inhalat. toxicity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>H331</td>
<td>H331</td>
<td></td>
</tr>
<tr>
<td>Target organ tox.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>H373</td>
<td>H370</td>
<td></td>
</tr>
</tbody>
</table>

Further testing on behalf of ECHA currently ongoing

Hazard potential: HXX0 - HXX5

ICH52021 - Hydrogen storage in LOHCs - ID5 - 21.09.2021
Handling hydrogen without its volatility and flammability is one of the major advantages of the LOHC technology

https://www.youtube.com/watch?v=9LnrNiHC_34
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StoragePLANT: LOHC Hydrogen Storage System
A scalable solution – applied process is state of the art in large scale hydrogenation at refineries

<table>
<thead>
<tr>
<th>StoragePLANT 5tpd</th>
<th>StoragePLANT 20tpd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen capacitya</td>
<td>5 t/d // 210 kg&lt;sub&gt;H2&lt;/sub&gt;/h</td>
</tr>
<tr>
<td>LOHC outputa</td>
<td>4,500 l/h</td>
</tr>
<tr>
<td>Heat productiona</td>
<td>1,900 kW&lt;sub&gt;th&lt;/sub&gt;</td>
</tr>
<tr>
<td>Load range</td>
<td>30 – 100%</td>
</tr>
</tbody>
</table>

*under nominal load

- Larger systems in development: up to 100-200 tpd
- Tank size and position can be defined flexibly depending on the project setting
- Tanks can also be included in scope of customer

Footprint
- Skid-based

Inlet hydrogen stream
- 20 – 50 bar, 99.99 % purity

Inlet LOHC stream
- ≥ 0.1 barg

Power connection
- 400 V AC, 3 phase, 50 Hz
ReleasePLANT: LOHC Hydrogen Release System
Scalable centralized or on-site solution

ReleasePLANT 1.5tpd

- Larger systems in development: up to 100 tpd
- Optimized footprint suitable for application at HRS

- LOHC underground tanks in portfolio
- Tank size and position can be defined flexibly depending on the project setting
- Tanks can also be included in scope of customer

**ReleasePLANT 1.5tpd**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen outlet</td>
<td>1.5 t/d // 65 kg H₂/h</td>
</tr>
<tr>
<td>LOHC demand</td>
<td>1,400 l/h</td>
</tr>
<tr>
<td>Heat demand</td>
<td>780 kWth</td>
</tr>
<tr>
<td>Load range</td>
<td>50 – 100 %</td>
</tr>
<tr>
<td>Footprint</td>
<td>Skid-based</td>
</tr>
<tr>
<td>Inlet LOHC stream</td>
<td>≥ 0.1 barg</td>
</tr>
<tr>
<td>Power connection</td>
<td>400 V AC, 3 phase, 50 Hz</td>
</tr>
</tbody>
</table>

*under nominal load

*I*CHS2021 - Hydrogen storage in LOHCs - ID5 - 21.09.2021
HRS Erlangen, Germany: LOHC-based Green Hydrogen Value Chain for H2 Mobility

Project description

• Implementation of first Hydrogen Refueling station to be supplied via LOHC
• Opening in mid 2021 in Erlangen, supported by public funding (by State of Bavaria)
• Worldwide first underground storage of 1.5 tons of hydrogen via LOHC
• Hydrogen quality according to ISO 14 687-2

Key Partners

Easy logistics
Minimal footprint
High safety due to absence of molecular hydrogen
Large amounts of H2 stored on site
Project Blue Danube: A pan-European supply chain for green hydrogen in the Danube region
Hydrogen-LOHC distribution via river Danube from South-East Europe to Austria and Germany
Assessment of different hydrogen transport options

Advantages of H2 transport in LOHC river ships
- Transport in existing infrastructure
- Usage of existing transport routes
- Large inland transport capacity
- Safe transport

Convoys on river Danube: 1 push-boat and 2 barges

186,000 kg H₂

Text highlights:
- Project Blue Danube
- Pan-European supply chain
- Hydrogen-LOHC distribution
- Danube region
- South-East Europe to Austria and Germany
- Assessment of different hydrogen transport options

Table highlights:
- Conditioning
  - Ammonia (NH₃)
  - Liquid hydrogen
  - Compressed gaseous hydrogen
  - LOHC

- Transport mode/infrastructure
  - Hydrogen pipeline
  - Gas grid injection
  - Ship/barge
  - Rail
  - Truck

Key Partners:
- Verbund
- Siemens Energy
- Bayernwerk
Improved cost competitiveness of LOHC technology in complex logistic chains

Archetype 2:  Mid-scale continental – year 2035 –

- 20 tpd
- 20 tpd
- ~1,428 km via vessel + ~350 km via train
- ~12 days per roundtrip (vessel) + ~0.8 days (train)
- 1,570 m³ (vessel) + 2,700 m³ (train)
- 3 vessels + 30 wagons/train
- 23,000 m³ of storage capacity (total)
- 12,030 t LOHC in the system

LOHC – BT

Ammonia

Liquified H₂

Archetype 2 mid-scale continental

[EUR/kg H₂]
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Hydrogenious und Ostensjo Rederi have founded a Joint Venture in Norway for the development of LOHC-driven ships

Development and demonstration of a Multi-MW emission-free drivetrain on the basis of LOHC technology

**New Joint Venture**

- Low cost hydrogen distribution
  - Use of existing fossil fuel infrastructure

- Low cost on-board storage
  - Use of existing fossil fuel storage tanks at ambient conditions

- Fast and familiar fueling process
  - Use of a liquid as a fuel

- High safety
  - Minimal amount of molecular hydrogen

**ICHS2021 - Hydrogen storage in LOHCs - ID5 - 21.09.2021**

**Hydrogenious LOHC Technologies and Østensjo Group Join Forces and Tread a Novel Path Towards Safe Zero-Emission Shipping**

*By FuelCellsWorks | July 2, 2021 | 7 min read (7188 words)*
LOHC Technology enables safe & dense Handling of hydrogen onboard

1 MW FC requires 60 kg/h; 350 m3 of LOHC is required for 14 days @ 1 ton H2 p.d.

**Conventional (existing) fuel tanks**
- Diesel-like liquid
- Stored at ambient conditions
- Liquid down to -35 °C
- Hardly flammable
- Non-explosive

**Minimal amount of molecular hydrogen**
- Hydrogen release only in presence of catalyst and heat

**Refueling by pumping a liquid**
- Fast refueling
- Use of conventional pumps
- Utilization of existing bunkering terminals
- Cargo during refueling possible

**H2 supply for different propulsion concepts**
- PEM-FC or SOFC (future)
- Dual or single fuel ICE

**Use of conventional fuel tanks**
- Diesel-like liquid
- Stored at ambient conditions
- Liquid down to -35 °C
- Hardly flammable
- Non-explosive

**H2 release unit**
- Hydrogen release only in presence of catalyst and heat

**Electric propulsion**
- PEM-FC or SOFC (future)
- Dual or single fuel ICE

**Cargo during refueling possible**
- Use of conventional fuel tanks
- Diesel-like liquid
- Stored at ambient conditions
- Liquid down to -35 °C
- Hardly flammable
- Non-explosive

**Hydrogen in LOHCs**
- Conversion of hydrogen to liquid
- Safe and dense handling of hydrogen onboard
- Refueling by pumping a liquid
- Fast refueling
- Use of conventional pumps
- Utilization of existing bunkering terminals
- Cargo during refueling possible

**H2 supply for different propulsion concepts**
- PEM-FC or SOFC (future)
- Dual or single fuel ICE
We enable a safe and efficient hydrogen economy!