Wasserstoff als Energiespeicher und Power to Gas

Uwe Würtenberger, Linde Clean Energy
Frankfurt, 27th March 2014
Contents

1. Innovation at “Linde Clean Energy”
2. Hydrogen technology a part of future energy systems
3. Hydrogen storage systems, development status and applications
4. Economics of Hydrogen storage
5. Status of pilot- & demonstration projects
The Linde Group
Headquartered in Munich, Germany

Linde Gas

Product Range
- Oxygen, nitrogen, argon
- Acetylene and other fuel gases
- Welding/ shielding gases
- Carbon oxide
- Hydrogen
- Medical gases
- Rare gases
- Ultra-high purity gases
- Gas application services

Linde Engineering

Comprised of two main divisions with 2013 revenue of € 16.7 billion

Product Range
- Petrochemical plants
- Natural gas processing plants
- Gas processing plants
- Hydrogen & synthesis gas plants
- Adsorption plants
- Cryogenic plants (e.g. ASU)
- Biotechnological plants
- CO₂ purification & liquefaction plants
- Plant components & modules
Linde has a wide portfolio of energy topics in the base business, as well as the Clean Energy arena.

<table>
<thead>
<tr>
<th>Energy value chain</th>
<th>Energy extraction</th>
<th>Energy conversion</th>
<th>Energy transport, storage and usage</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fossil (gaseous)</strong></td>
<td>Baseload LNG</td>
<td>Floating LNG</td>
<td>GTL</td>
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<tr>
<td></td>
<td>Unconv. gas</td>
<td>Cogeneration</td>
<td></td>
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<tr>
<td><strong>Fossil (liquid, solid)</strong></td>
<td>N₂ EOR</td>
<td>NRU</td>
<td>Clean coal</td>
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<tr>
<td></td>
<td>CO₂ EOR</td>
<td>OxyFuel</td>
<td>PCC</td>
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<tr>
<td><strong>Renewable</strong></td>
<td>Geothermal</td>
<td>Heat recovery</td>
<td>Biomass conv.</td>
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<td></td>
<td>Solar-thermal</td>
<td>Green Hydrogen</td>
<td>Wind energy</td>
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</tbody>
</table>
Linde covers the entire hydrogen value chain with in-house technology & developments.

<table>
<thead>
<tr>
<th>Production</th>
<th>Supply/ Storage</th>
<th>Compression/ Transfer</th>
<th>Dispenser</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional (e.g. SMR)</td>
<td>CGH$_2$ storage</td>
<td>Ionic compressor</td>
<td>350 bar</td>
</tr>
<tr>
<td>Green (e.g., BtH*, Ely)</td>
<td>LH$_2$ storage</td>
<td>Cryo pump</td>
<td>700 bar</td>
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<tr>
<td></td>
<td>Onsite SMR</td>
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<tr>
<td></td>
<td>Onsite Electrolysis</td>
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</tbody>
</table>

* Biomass to Hydrogen
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Why energy storage?

Electricity-based fluctuating renewables (Wind+PV) continue rapid growth:
- >12% of electricity provision in Germany by 2012 (74 TWh)
- Germany has 31 GW wind and 32 GW PV installed (+7.5 GW PV in 2012!)
- until 2020, 100-150 GW wind+PV expected; grid load is only 60-80 GW!
- High excess electricity during high-wind times; full backup capacity during low-wind times

Energy storage can shift electricity from overrun to underrun situations:
- Improved integration of renewables
- Provision of strategic energy reserves
- Lower grid extension efforts
- Increased security of supply
No „one-fits-all“ solution to energy storage in sight!

Requirements for storage systems:

- High efficiency (price arbitrage)
- Low power-specific costs (short-term storage)
- Low storage-specific costs, low self-discharge (long-term storage)
- Load rangeability and quick reaction (control reserve)
- High cycle / calendaric life
- Compact, safe, simple, scalable
- …

→ No technology can fulfill all requirements
→ Different applications will require different storage technologies

<table>
<thead>
<tr>
<th>Technology class</th>
<th>Fossil power</th>
<th>Renewables</th>
<th>Transmission</th>
<th>Distribution</th>
<th>Customers services</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumped hydro</td>
<td></td>
<td></td>
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<tr>
<td>Compressed air</td>
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<tr>
<td>Electrochemical</td>
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<tr>
<td>Chemical</td>
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<tr>
<td>Electro-magnetic</td>
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<tr>
<td>Thermal</td>
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</table>

Source: European Association for the storage of energy (EASE)

Strengths of hydrogen energy storage

Unlike other storage types, hydrogen can:

- store large amounts of energy at reasonable costs (~170 GWh\textsubscript{LHV} in one typical salt cavern)
- facilitate seasonal storage (weeks to months)
- create cross-links from renewable electricity to other sectors (fuels, chemicals)
Versatile usage options for hydrogen in the energy system
Highest lever in mobility and industry

1 kWh wind power

Wind park

Electrolysis

~65%*

0.65 kWh H2

~100%*

Hydrogen Storage

~80%*

Methanation

0.2-0.4 kWh Power
→ 0.3-0.6 kWh NG

0.65 kWh SMR-H2
→ 0.8-1 kWh NG

~2 km travelled (car)
→ ~1 kWh Diesel

0.5-0.6 kWh NG

Power grid

~65%*

~100%*

~80%*

Power generation

Mobility

Industry

* efficiency based on lower heating value
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# Hydrogen generation via electrolysis

## Technology types, advantages and drawbacks

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<thead>
<tr>
<th></th>
<th>Alkaline electrolyser</th>
<th>PEM electrolyser</th>
<th>Solid oxide electrolyser</th>
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<tbody>
<tr>
<td></td>
<td>AEL</td>
<td>PEMEL</td>
<td>HTEL</td>
</tr>
<tr>
<td><strong>Advantages</strong></td>
<td>• Established</td>
<td>• High current density</td>
<td>• Low electricity consumption</td>
</tr>
<tr>
<td></td>
<td>• Long durability</td>
<td>• High pressurization Possible</td>
<td>• Potentially high efficiency</td>
</tr>
<tr>
<td></td>
<td>• No precious metal catalyst</td>
<td>• Part load &amp; peak load ability</td>
<td>• No precious metal catalyst</td>
</tr>
<tr>
<td></td>
<td>• Pressurization possible</td>
<td>• High H2 purity</td>
<td>• Potential for high current density</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Simple system Configuration</td>
<td>• Possible co-electrolysis (CO2/ H2O/ H2, CO2, dual operation as fuel cell)</td>
</tr>
<tr>
<td><strong>Drawbacks</strong></td>
<td>• Relatively low current density</td>
<td>• Precious metal catalyst</td>
<td>• Still R&amp;D phase</td>
</tr>
<tr>
<td></td>
<td>• Corrosive electrolyte</td>
<td>• High investment cost</td>
<td>• Unproved durability</td>
</tr>
<tr>
<td></td>
<td>• Complex system</td>
<td>• Insufficient durability (catalyst degradation w. dynamic operation)</td>
<td>• Complex heat Management</td>
</tr>
</tbody>
</table>

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**Source:** Siemens

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**Source:** Hydrogenics

**Source:** PEM stack from Siemens

**Source:** Solid oxide stack from Topsoe Fuel cell
Electrolysis methods, capacity \([\text{Nm}^3/\text{h}]\) on technology radar

Yet, market is dominated by few players today.
Small- and medium scale hydrogen storage

- LH$_2$ and CGH$_2$ storage state of the art
- LH$_2$ needs energy intensive liquefaction (-250 °C)
- Chemical storage / sorption technologies: heat release to ingest hydrogen; heat needed to release hydrogen; cycling issues
- Compressed gaseous storage: easy and reliable solution (but, hazard potential/perception)
- Volumetric density in similar range for all systems 20-50 kg/Nm$^3$)
Large-scale hydrogen storage
Salt caverns

- Salt caverns are **artificial** cavities in salt domes
- Used extensively today for storage of natural gas, oil and chemicals; also hydrogen caverns exist
- Typical volume ~500,000 m³; typical pressure range 60-200 bar → filled with hydrogen, one cavern can store **about 170 GWh**
- Possible only where suitable salt structures exist (e.g. Northern Germany)
- Lead time of up to 10 years
- Well-suited for seasonal storage through low specific storage cost
Costs of hydrogen storage

Benchmarking

- Cavern storage is 3-4 orders of magnitude cheaper than batteries
  → Best suited for long-term storage
- Liquid hydrogen cheapest aboveground storage technology

Investment costs of hydrogen storage capacity* and comparison

* Storage system only (no electrolysers, turbines, etc.); based on lower heating value; rough estimations
## NG Grid Injection
Comparison H₂ and CH₄/SNG (Methanation)

<table>
<thead>
<tr>
<th></th>
<th>Power-to-H₂ (NG grid injection)</th>
<th>Power-to-SNG (NG grid injection)</th>
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</thead>
<tbody>
<tr>
<td><strong>Gasnetzeinbindung</strong></td>
<td>Eingeschränkt (max. 1-10 vol.% Beimischung)</td>
<td>Uneingeschränkt</td>
</tr>
<tr>
<td><strong>Hauptbetriebsmittel</strong></td>
<td>Strom</td>
<td>Strom + CO₂</td>
</tr>
<tr>
<td><strong>Wirkungsgrad (Hᵳ)</strong></td>
<td>~65%</td>
<td>~50% (+Hochtemperatur-Wärme)</td>
</tr>
<tr>
<td><strong>Dynamische Betriebsweise</strong></td>
<td>Stand der Technik</td>
<td>F&amp;E-Bedarf (Methanisierungsreaktor); ggf. abh. von Speicherkapazität CO₂</td>
</tr>
<tr>
<td><strong>Standortkriterien</strong></td>
<td>Stromnetzanbindung, Gasnetzanbindung</td>
<td>Stromnetzanbindung, Gasnetzanbindung, CO₂-Quelle</td>
</tr>
<tr>
<td><strong>Potenzial/Einschränkungen</strong></td>
<td>Beimischquote; aktuell ca. 2-18 TWh (→ graduelle Erhöhung)</td>
<td>CO₂-Verfügbarkeit (2030: ~100 TWhₜₘₑ/ₐ aus Biogas upgrading)</td>
</tr>
<tr>
<td><strong>Wirtschaftlichkeit</strong></td>
<td>Ohne polit. Unterstützung nicht wirtschaftlich</td>
<td>Ohne polit. Unterstützung nicht wirtschaftlich</td>
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</table>
Industrial usage of hydrogen
Markets and applications

- Further applications: (<1000 Nm³/h): Float glas, food processing, generator cooling
- Only about 5% of H₂ is transported (rest produced on site)

Sources: DOE, Fair-PR

- After liquefaction <1%
  - Rocket Fuel
  - Semiconductor Industry (incl. Photovoltaic)

- Refineries 31%
  - Hydrocracking
  - Hydrotreating

- Chemical Industry 63%
  - Ammonia 53% (Urea, Fertilizer)
  - Methanol 8%
  - Polymers 2% (Caprolactam, Adipic Acid ➔ Nylon)
  - Polyurethanes (MDI and TDI as Precursor for)

- Metal Processing 6%
  - Direct Reduction of Iron Ore
  - Forming & Blanketing Gas

- ~ 1500 TWh/a or ~ 300 mill. fuel cell cars

app 500 bill. Nm³/a global
Why Hydrogen as fuel?

Hydrogen offers…

- CO2 reduction potentials
- Diversification of primary energy sources
- Zero emissions at the tailpipe
- Multiple application usages*

* Especially compared to electricity based transportation

...just like batteries
Hydrogen as fuel
Rationale

Transition to hydrogen-powered transport
driven by
– environmental legislation,
– crude oil independency
– feedstock flexibility
– zero-emission mobility
– range and fuelling convenience

All major OEMs announced commercialization between 2014 – 2020

Key application areas
— Cars
— Buses
— Fork lift trucks
— Backup/remote power

FCEV for low emissions and high range

OEM Commercialization pipeline

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</table>
Hydrogen production pathways
Intermittent power to hydrogen (power to gas)

Basic flow chart: Wind to hydrogen

Wind power → Grid → Electrolysis & Compression → Dispenser → Application / Usage

Vattenfall HafenCity, Hamburg
# Linde’s advanced hydrogen fuelling technologies

## Key components for compression

### The Ionic Compressor
- High throughput of 35 kg/h @ 900 bar\(^1\)
- Energy consumption reduced by 25%\(^2\)
- Very small number of moving parts (liquid piston)
- Reduced wear and long service life
- Four times longer maintenance intervals*\(^*\)
- Fulfils industry standard SAE J 2601

### The Cryo Pump
- Very high throughput of up to 120 kg/h @ 900 bar
- Energy consumption reduced by 70%\(^2\)
- Hydrogen with highest purities
- No additional cooling system
- High reliability, little maintenance effort and low costs
- Fulfils industry standard SAE J 2601

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\(^1\) For one system. Modular setup allows for higher throughputs.

\(^2\) In comparison to a conventional piston compressor.
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Use cases for electrolysis Hydrogen
No viable economic today

Market situation today

Energy (NG grid)

- NG
- Bio-methane
- Electrolysis-H2
- Methanised H2
- Energy cost (€/MWh)

- Gap

Energy (Power via CCGT)

- Spot market
- Wind power
- Electrolysis-H2 (central, CCGT)
- Electricity cost (€/MWh)

- Gap

Industry (trailor delivery)

- NG-SMR-H2
- Biogas-SMR
- Electrolysis-H2 (onsite)
- H2 cost (€/kg)

- Gap

Mobility (onsite)

- NG-SMR-H2 (onsite)
- Biogas-SMR (onsite)
- Electrolysis-H2 (onsite)
- H2 cost* (€/kg)

- Gap

Economics of Electrolysis H2

- Use of electrolysis H$_2$ cannot compete against alternatives today
- Smallest gap in mobility (compared to Biogas-SMR)
- Largest gap in power generation
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Pilot project „H2BER“ (Berlin-Brandenburg Airport)
The „Swiss Army Knife“ of hydrogen energy

- Total, Linde and McPhy erect a hydrogen refuelling station including electrolysis from windpower and a trailer filling plant at the new Berlin airport to be operated in 2014.
- Electrolysis provided by McPhy (500 kW\text{el}; hydrogen output \(\sim 100 \text{Nm}^3/\text{h}\) or 9 kg/h)
- Hydrogen fuelling station operated by Total (350/700 bar; cars and buses)
- Linde built ionic compression, storage and trailer filling plant to take off excess hydrogen or supply additional hydrogen
- Funding via National Innovation Programme Hydrogen and Fuel Cells
Pilot project „Energiepark Mainz“
Scaling up to grid relevance

Key facts

- Pilot project for hydrogen electrolysis, storage and usage in Mainz by Stadtwerke Mainz, Linde, Siemens and Hochschule RheinMain to be operated by 2015
  - Siemens PEM electrolysis with up to 6 MW peak power intake
  - Linde novel Ionic Compressor for flexible and energy-efficient operation
  - Pressurised storage ~1000 kg (~33 MWh)
  - Hydrogen trailer filling station
  - NG grid injection (CCGT power plant)
- Power from various sources (wind power, control reserve, spot markets)
- Targets:
  - Management of local grid bottleneck
  - Testing and gaining operational experience with components
  - Intelligent control and market integration

Funded by:
Conclusions

— For energy system with large amount of wind and PV we need energy storage to level out the fluctuations
— Only long term energy storage can provide security of supply
— Hydrogen storage caverns are specifically 3-4 orders of magnitude cheaper than batteries
— Hydrogen can build new bridges in the energy system (wind → mobility, industry, natural gas)
— Technology is available; cost reduction & efficiency improvement are underway
— No economic case today; favourable regulations needed to trigger market introduction

→ Linde is a strong and innovative partner on hydrogen technology and handling
Thanks for your attention.

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Linde Innovation Management

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LeadIng.

THE LINDE GROUP