Conclusion / Next Steps

IDEALHY partners are actively progressing hydrogen liquefaction and associated parts of the value chain

IDEALHY has shown that the energy used for hydrogen liquefaction can be comparable to that of compression, and that construction of such a plant is feasible in the short to medium term.

Crucial aspects for success of the first plant include:

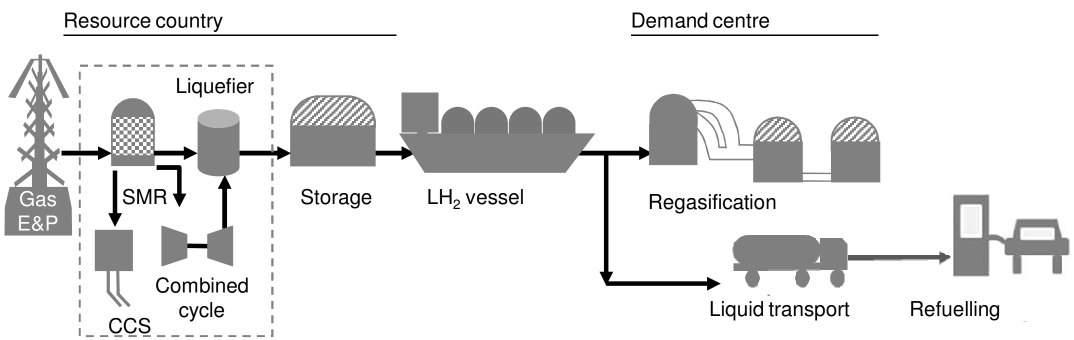
- Thorough testing at experimental and pilot scale before plant construction, in order to reduce the technical risk associated with novel components
- Effective liaison with equipment suppliers to ensure availability of machines

The success of large-scale hydrogen liquefaction depends on good links with the developing market.

Need to maximise the potential for LH_2 for large-scale hydrogen supply

- Active participation in growing the market and infrastructure for fuel cell buses
- Selection of the optimal plant location
  - Including supply of (low-carbon) hydrogen and a market for LH_2
  - Collaboration with partners in upstream / downstream segments required (including shipping)
- Exploration of other applications of liquid hydrogen e.g. industry

Efficient liquid hydrogen supply enables transport of low-CO_2 energy and the mass roll-out of fuel cell vehicles. IDEALHY has shown that this can be a reality in the medium-term future.



Integrated SMR with Liquefaction

idealhy

Integrated Design for Demonstration of Efficient Liquefaction of Hydrogen

Enabling liquid hydrogen as a means of distribution of low-carbon energy

New Energy World JU
fuel cells & hydrogen for sustainability

Grant Agreement No. 278177

IDEALHY shows the potential of liquid hydrogen to store low-carbon energy at large scale and transport it from resource to demand areas

- A hydrogen liquefaction process has been designed for plants between 40 and 200 tonnes per day
  - Taking into account safety and risk management at all stages of the liquid hydrogen (LH_2) value chain
  - While keeping investment cost to a minimum.
- The design reduces the liquefaction energy requirement by half
  - Reducing liquefaction cost to competitive levels
  - Greenhouse gas (GHG) emissions levels can be comparable with compressed hydrogen
- This permits the growth of hydrogen infrastructure beyond the potential of compressed hydrogen
  - Enabling efficient supply of hydrogen to large vehicle refuelling stations
- A strategic plan was made for construction of a demonstration plant
  - Options for plant location discussed
  - Hydrogen supply and market development included
  - Next steps and possible partners identified

Timeline: November 2011 – October 2013

Detailed information and results available at www.idealhy.eu

The research leading to these results has received funding from the EU's 7th Framework Programme (FP7/2007-13) for the Fuel Cells and Hydrogen Joint Technology Initiative, under grant agreement n° 278177.

Roadmap generated for demonstration plant, including options for location

IDEALHY sub-processes / components at different stages of maturity

Suppliers need convincing that their components will be needed in the near future

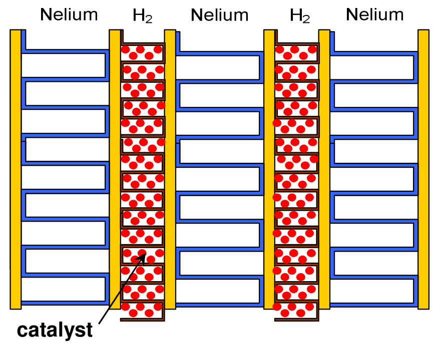
Experimental test stands recommended precursor to commercial demonstration

Test stands R&D / subsidised
↓
40 tpd Commercial demo
↓
>600 tpd Fully commercial

- Commercial and technical de-risking through test stand stage (3-4 years)
  - Component commercialisation and demo plant plans proceeding in parallel
  - stands can be in different locations, with different test schedules and/or involving a range of suppliers
- Commercial plant construction could start in 2017
  - favoured location Norway
  - resource country within reach of demand areas
- Integrated demonstration needed , including LH_2 use by e.g. bus depots
  - collaboration planned with IGCs, OEMs, oil companies, utilities etc.
- Smallest plant compatible with effective demonstration of technology: 40 tonnes per day
  - proposed design permits efficient part-load operation in initial phase, to maximise chances of commercial off-take of LH_2
  - ramp up of production planned as LH_2 market develops

Technical challenges also remain

- Further optimisation of *ortho-para* conversion in heat exchanger



Component development needed

- High-pressure gas-bearing turbines for cryogenic expansion
- Large compressor / expander pairs
  - Very high speed, magnetic bearings, in vacuum cold box
- High-speed turbocompressors for low molecular weight gas (He/Ne mix 'Nelium')

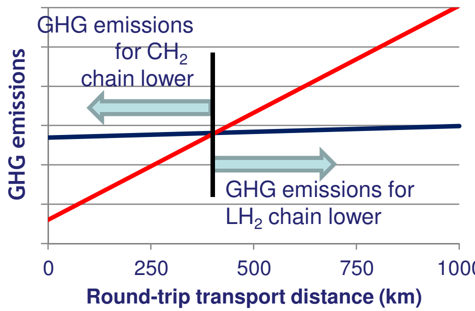
Life cycle analysis demonstrates advantages of liquid hydrogen supply chain, and risk / safety management is in hand

Liquid hydrogen supply competitive with gaseous hydrogen over entire supply chain

Analysis includes primary energy inputs, GHG emissions and total internal costs

- Benchmarked against gaseous distribution and gasoline baseline
- Emissions & costs lower for LH_2 distribution compared with CH_2 beyond threshold distance

Delivery emissions LH_2 vs. CH_2

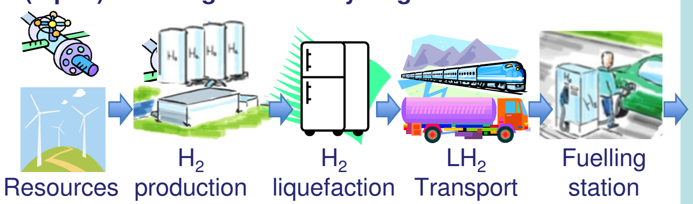


IDEALHY has improved understanding of LH_2 hazards

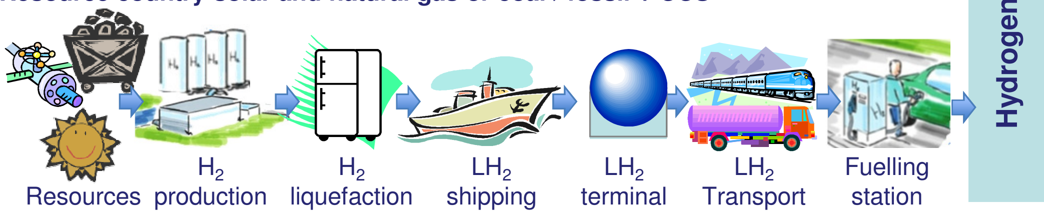
Existing information on HSE which is relevant to large-scale LH_2 is very limited

- Two hazard identification studies and incident reviews carried out:
  - Transport by road tanker and storage at a refuelling station
  - Liquefaction of gaseous hydrogen and storage of LH_2 at production site
- Each incident analysed to identify both **cause** and **consequences**
  - Equipment failure / incorrect operation primary causes
  - Accumulation / dispersion of LH_2 main consequence
- Models used to assess progress of incidents and risk mitigation procedures developed

Demand country wind and (liquid) natural gas + CCS hydrogen



Resource country solar and natural gas or coal / fossil + CCS

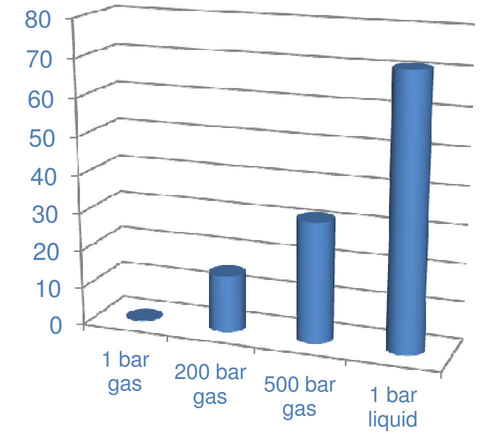


Liquefaction offers efficiency and cost advantages for distribution and storage of hydrogen

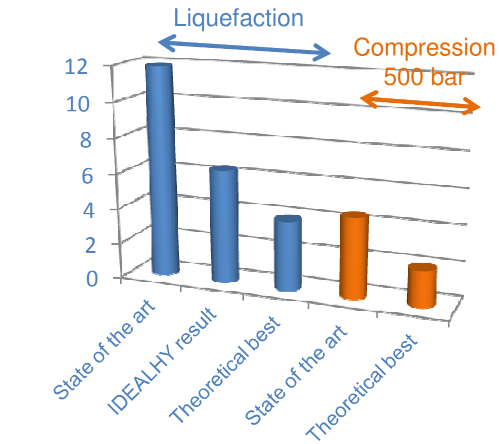
In the absence of a pipeline network, liquid hydrogen can be the most economical way of distributing large quantities of hydrogen to the end user.

In the wider field of hydrogen as an energy vector, liquid hydrogen (LH_2) could mean efficient transport of CO_2-free energy to where it is needed.

Hydrogen density, kg/m³



Energy use, kWh/kg H_2



Liquefaction energy approaches that of compression

For transport, the advantages include:

- Fewer distribution trucks on the road thanks to 4x greater capacity
  - Liquid: ±4000kg (500 bar gas: ±900kg)
- Both storage and equipment for compression to 700 bar (for refuelling) are more compact / cheaper using LH_2

Liquid supply to retail stations

LH_2 station in Berlin built by Linde

Long-distance energy transport

LH_2 ship concept (Kawasaki Heavy Industries)

A liquid hydrogen supply chain supports planned mass roll-out of fuel cell vehicles

Logistics of compressed hydrogen supply become challenging for large refuelling stations (1,500kg hydrogen per day, comparable to existing large petrol stations)

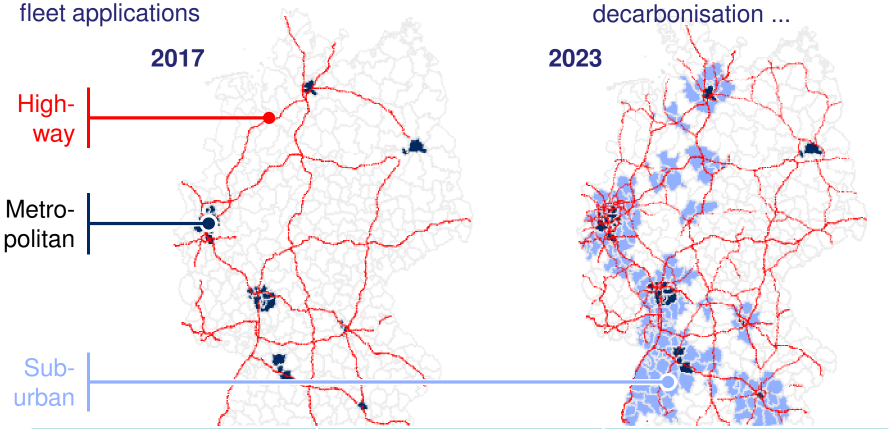
- Such a station would require 3-5 deliveries per day of compressed hydrogen at 200 bar
- Liquid hydrogen delivery is particularly appropriate for bus/fleet depots because of high throughput

German H2Mobility project leads the development of a hydrogen infrastructure in Europe, supporting ambitious CO_2 reduction aims

- The H2Mobility joint venture company plans over 400 retail stations by 2023
- LH_2 supplied stations could play major role as market and infrastructure expand
- Beyond H2Mobility there are possibilities in fuel cell buses and other fleet applications

LH_2 also enables further development of hydrogen as an energy vector

- LH_2 ship transport from resource country to demand centre
- Low-carbon hydrogen achievable through CCS at source
- Hydrogen available at demand centre for range of applications
  - e.g. mobility, industry, gas grid decarbonisation ...



No. of FCEVs (1000s)	~5	~150
No. of HRS	~100	~400

Planned roll-out of hydrogen stations in Germany (source: NOW)

Hydrogen liquefaction is historically high in power consumption, but IDEALHY shows that this can be halved while maintaining realistic cost targets

Existing plants were not constructed with efficiency as the main target, hence there is large potential for reduction in energy requirement of liquefaction:

- By increasing plant scale
- With more efficient process design
- Using more efficient components

Plant	Energy use, kWh/kg
Linde Ingolstadt (1992)	13.6
Linde Leuna (2007)	11.9
IDEALHY result	**6.4**

Further efficiency improvements are possible by integrating liquefaction with other processes such as LNG re-gasification

- Energy consumption is reduced if input pressure is higher

Theoretical analysis, process design and component development

- Functional schemes of efficient large-scale hydrogen liquefaction processes (existing and proposed) identified; boundary conditions and duty specifications established, existing schemes compared
- Large-scale liquefaction concept selected using mixed refrigerant cooling to 130 K
- Cryogenic cooling with two Brayton cycles, final expansion / liquefaction
- Cryogenic pipes, vessels and valves designed and tested
- Catalysis of *ortho-para* conversion within novel heat exchanger geometry tested
- Full plant design completed and layout drafted