Hydrogen Liquefaction and Storage

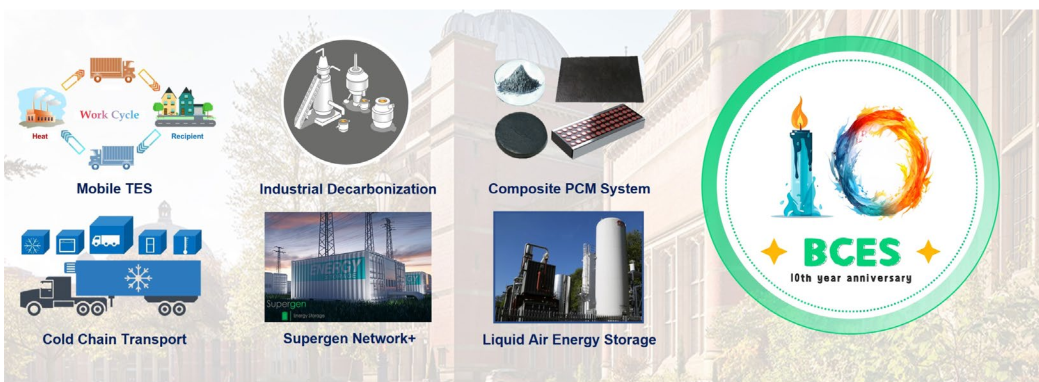
Recent Progress and Perspectives

Tongtong Zhang, Lejin Xu, Yixuan Huang, Yulong Ding

University of Birmingham Center for Energy Storage

*t.zhang.7@bham.ac.uk

www.birmingham.ac.uk/energystorage



Contents

UNIVERSITY OF BIRMINGHAM

- **Background**
  - The role of hydrogen in future energy systems
  - The needs for liquid hydrogen
- **Liquid hydrogen production, storage and transmission technologies and challenges**
  - Hydrogen liquefaction
  - Liquid hydrogen storage
  - Liquid hydrogen transportation
- **Economic aspects of liquid hydrogen**
- **Concluding remarks**

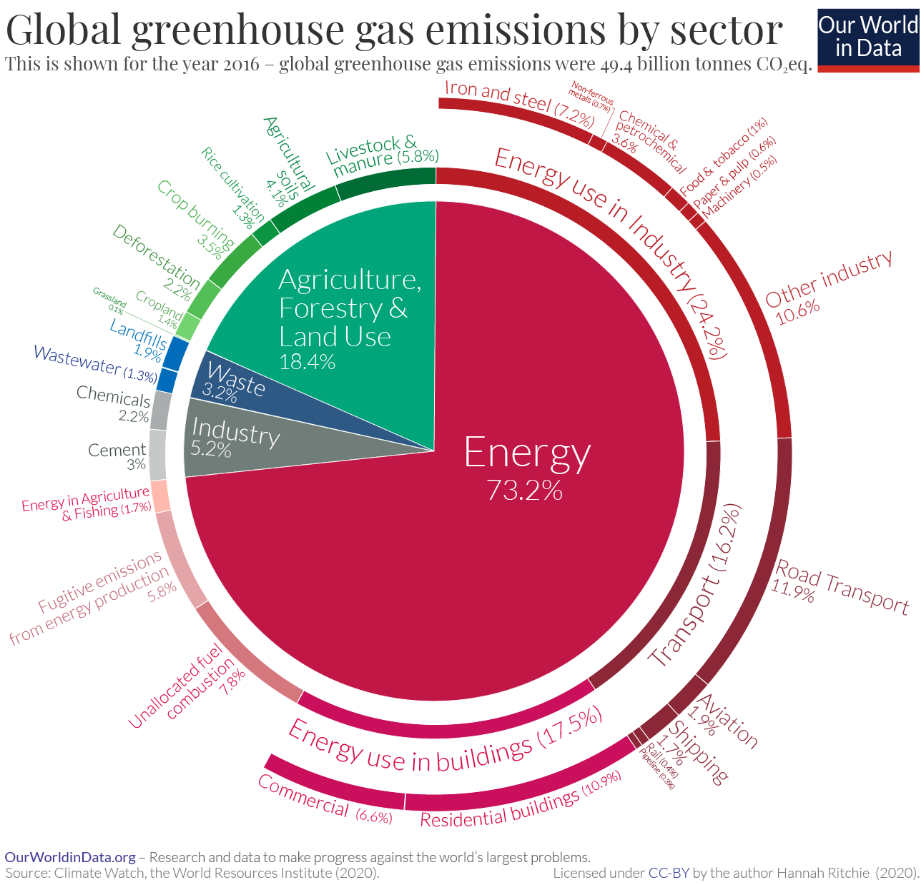
Contents

UNIVERSITY OF BIRMINGHAM

Background - The role of hydrogen in future energy systems (A)

UNIVERSITY OF BIRMINGHAM

Data Speak



Carbon Emission for Energy - 73.2%

- Energy Use in Building – 17.5%
- Energy Use in Transport – 16.2%
- Energy Use in Industry – 24.2%

Transport (16.2%): electrification & H_2 provide routes to decarbonisation

- Road Transport – 11.9%:
- Aviation – 1.9%
- Shipping – 1.7%
- Rail – 0.4%
- Pipeline – 0.3%

Hydrogen provides a route towards part of transport sector that is hard-to-decarbonise through electrification: heavy truck, medium to long haul aviation, long-haul shipping, etc.

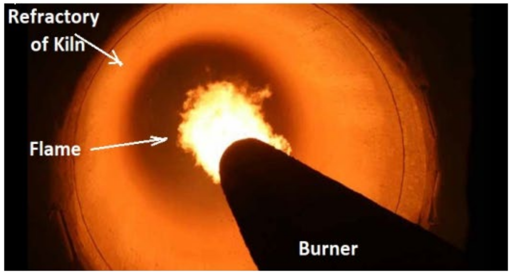
https://ourworldindata.org/

Background - The role of hydrogen in future energy systems (B)

UNIVERSITY OF BIRMINGHAM

Foundation industry - metal, glass, cement, ceramics, chemical & papermaking

Steel Industry – Ironmaking



Cement Industry – Rotary Kiln

Glass Industry – Glassware making

Ceramic Industry – Ceramic Firing Furnace

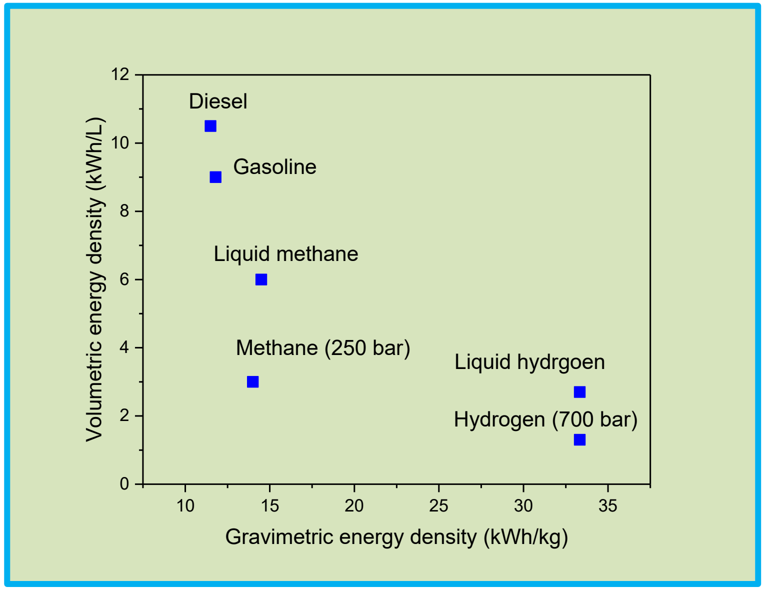
- High temperature, combination of continuous and batch operations
- Electrification is challenging due to little inertia; heat pumps do not work
- Waste heat abundant but with a low value chain
- Lots of small & medium sized, distributed companies using conventional technologies
- Crucial industrial sectors, matter to national security
- Low margin making the adoption of alternative fuels difficult for these industry

Hydrogen provides a route towards hard-to-decarbonise industrial sectors with carbon emissions of ~30%: direct emission (~5%) and energy related emission (~25%)

Background - The needs for liquid hydrogen

UNIVERSITY OF BIRMINGHAM

Liquid hydrogen has some salient characteristics



Liquid hydrogen application

- Liquid rocket fuel for rocketry applications
- Cool neutrons to be used in neutron scattering
- **Long-distance energy transmission**
- **Aviation technology**
- **Motor vehicles**

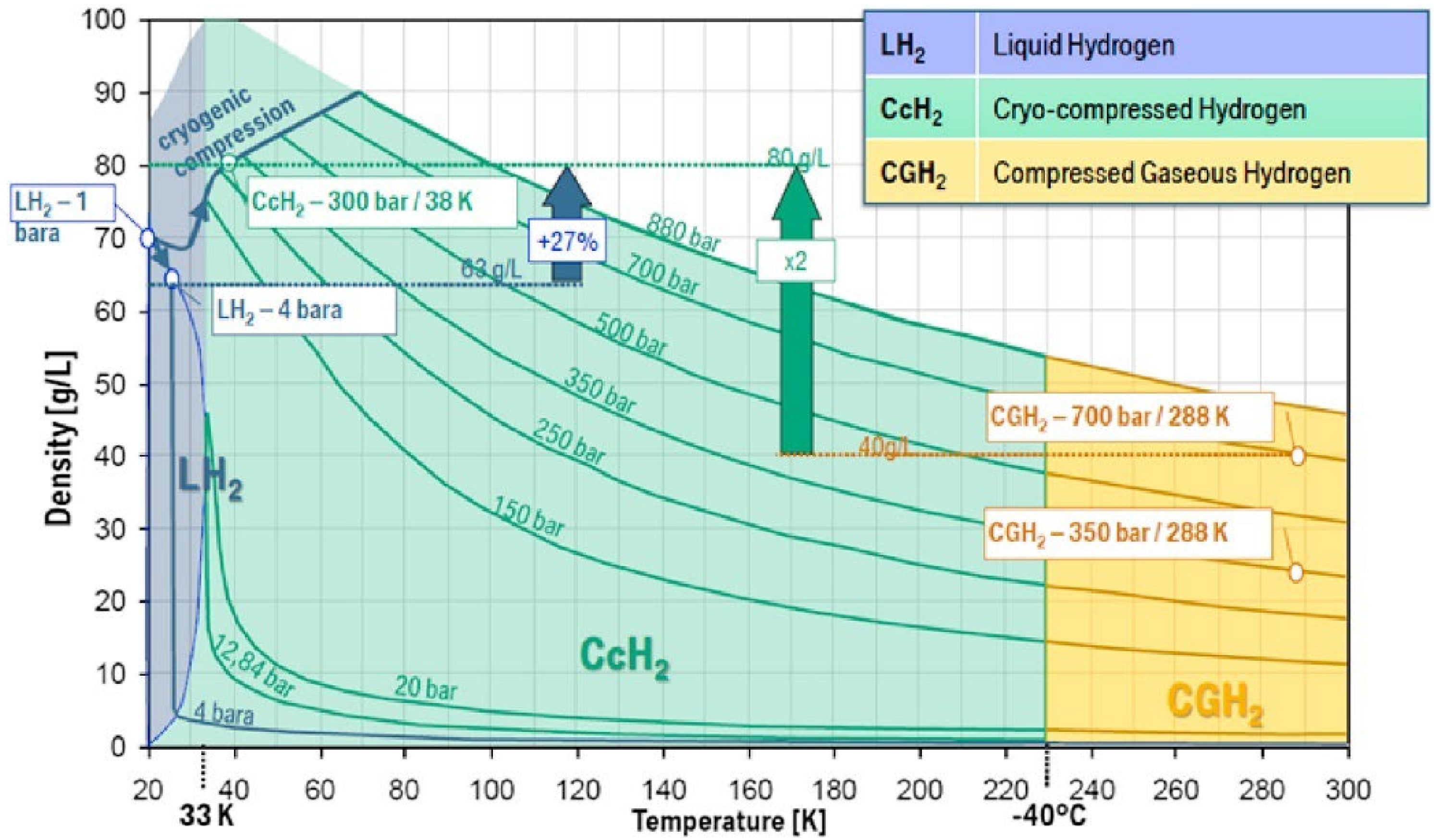
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY https://www.energy.gov/eere/fuelcells/hydrogen-storage

Contents

UNIVERSITY OF BIRMINGHAM

- Background
  - The role of hydrogen in future energy systems
  - The needs for liquid hydrogen
- Liquid hydrogen production, storage and transmission technologies and challenges
  - Hydrogen liquefaction
  - Liquid hydrogen storage
  - Liquid hydrogen transportation
- Economic aspects of liquid hydrogen
- Concluding remarks

Density as a function of temperature and pressure



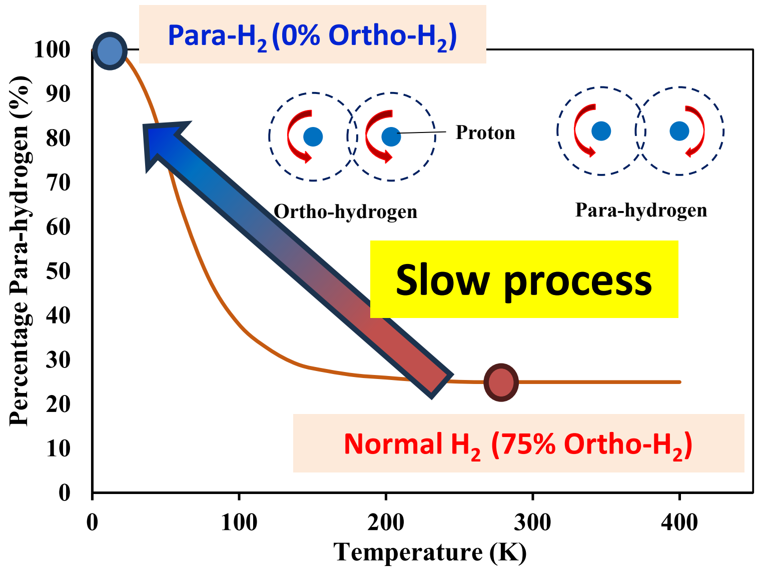
The challenges: Very low temperature, narrow operation temperature range even at high pressures

Tarhan & Çil (2021) Journal of Energy Storage, 40, 102676; Zhang et al. (2023) Renewable and Sustainable Energy Reviews, 176, 113204

Liquid hydrogen production, storage and transmission technologies and challenges - Hydrogen liquefaction

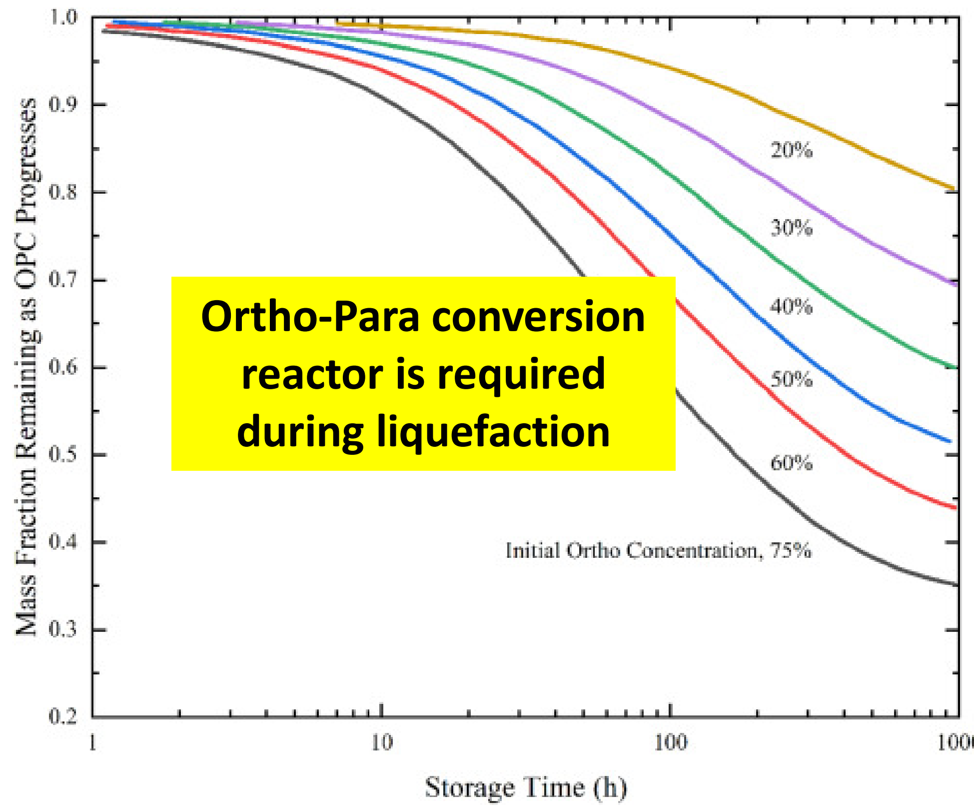
Ortho-Para Conversion

Equilibrium between Ortho-hydrogen (O) and Para-hydrogen (P)



Properties	Ortho-Hydrogen	Para-Hydrogen
Spin direction	Same direction	Opposite direction
Spin alignment	Parallel	Antiparallel
Energy state	Higher energy state	Lower energy state
Nuclear magnetic resonance (NMR) spectroscopy	Triplet	Singlet

O-P conversion heat generation



Aziz, M. (2021). Liquid hydrogen: A review on liquefaction, storage, transportation, and safety. Energies, 14(18), 5917.

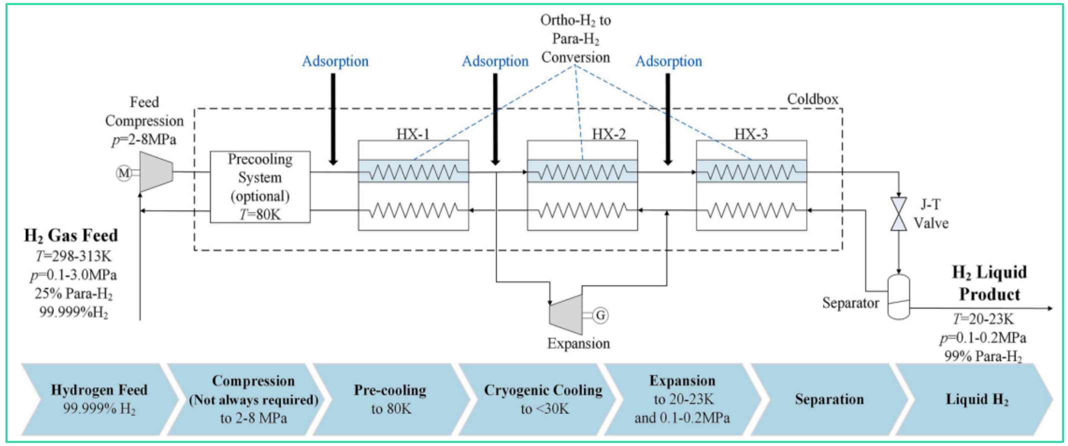
The challenges: Boil-off problem - The heat generation of 527 kJ/kg > the latent heat of liquid hydrogen vaporization of 446 kJ/kg

Zhang et al. (2023) Renewable and Sustainable Energy Reviews, 176, 113204

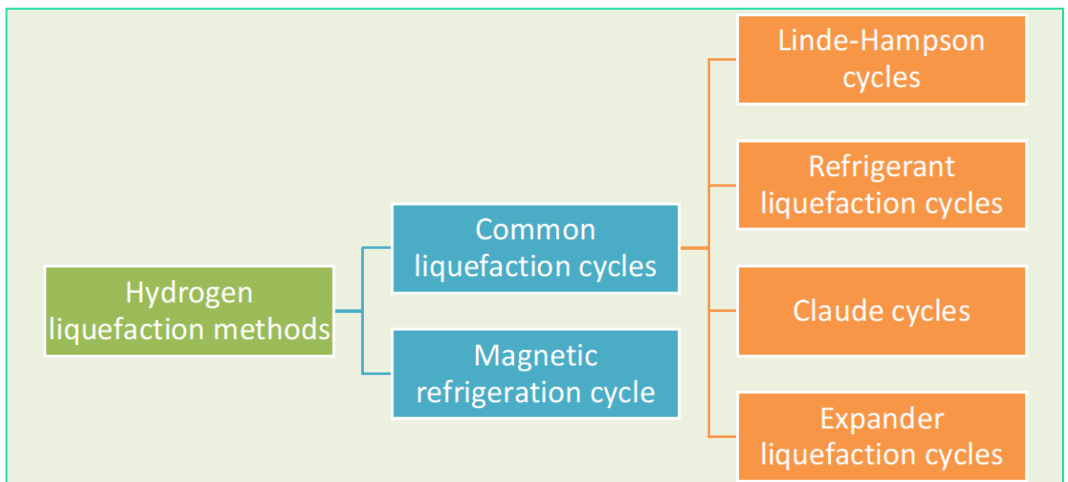
UNIVERSITY OF BIRMINGHAM

Hydrogen liquefaction technologies

A schematic hydrogen liquefaction process



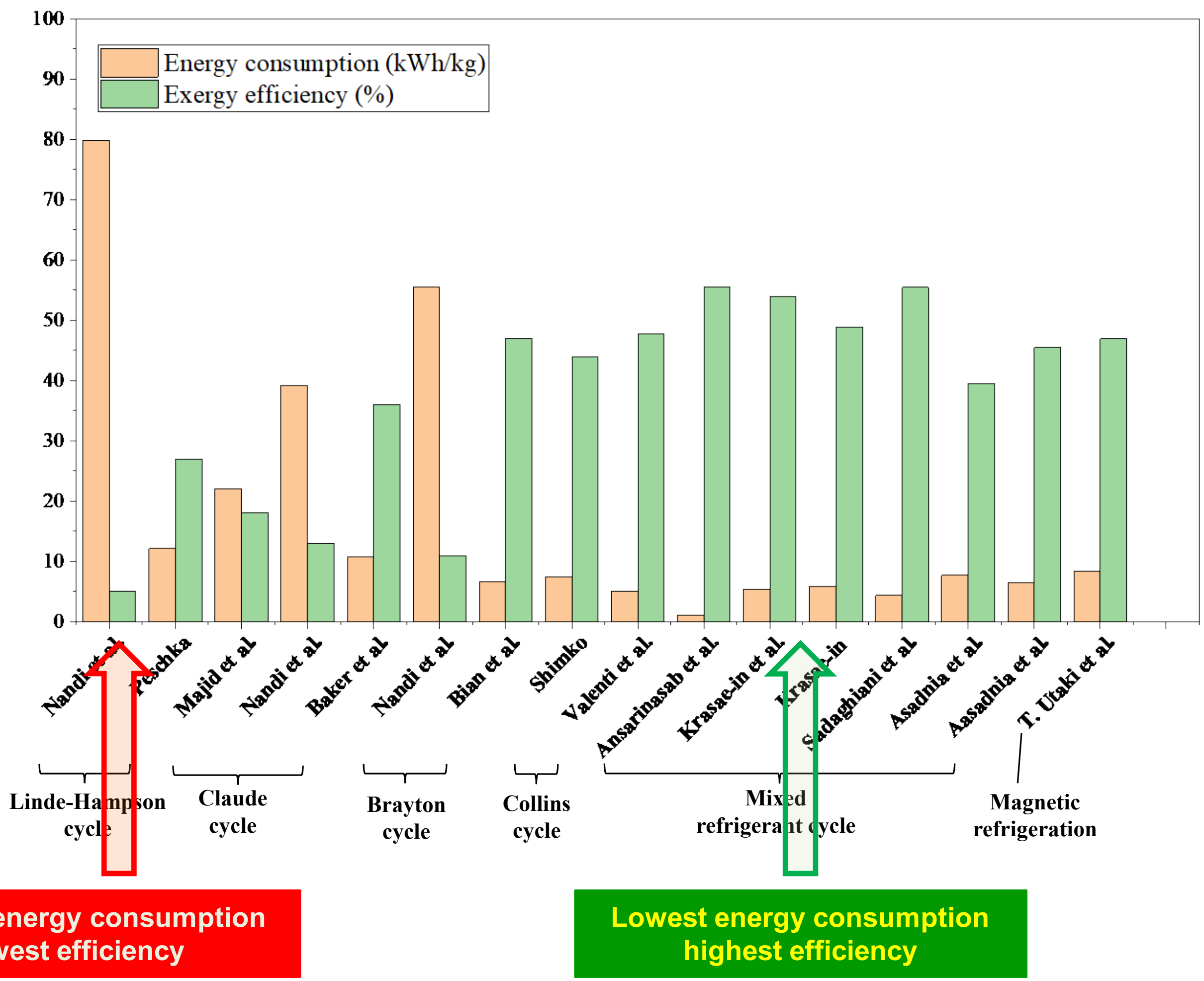
Liquefaction methods



Zhang et al. (2023) Renewable and Sustainable Energy Reviews, 176, 113204

UNIVERSITY OF BIRMINGHAM

Summary of hydrogen liquefaction cycles – comparison of efficiency and energy consumption



Zhang et al. (2023) Renewable and Sustainable Energy Reviews, 176, 113204

Energy consumption performance - comparison between theoretical and commercial hydrogen liquefaction

Classical theoretical cycles
>10 kWh/kgLH_2
(Linde-Hampson and Claude cycles)

Large plants in-service
13.83 kWh/kgLH_2
(on average)

Optimised liquefaction cycles
<10 kWh/kgLH_2
(expander liquefaction cycles)

Target for large-scale hydrogen liquefaction plants
6 kWh/kgLH_2
(US Department of Energy)

Minimum energy required
~3 kWh/kgLH_2
(thermodynamically ideal hydrogen liquefaction cycle)

Zhang et al. (2023) Renewable and Sustainable Energy Reviews, 176, 113204

Future trend in hydrogen liquefaction technologies

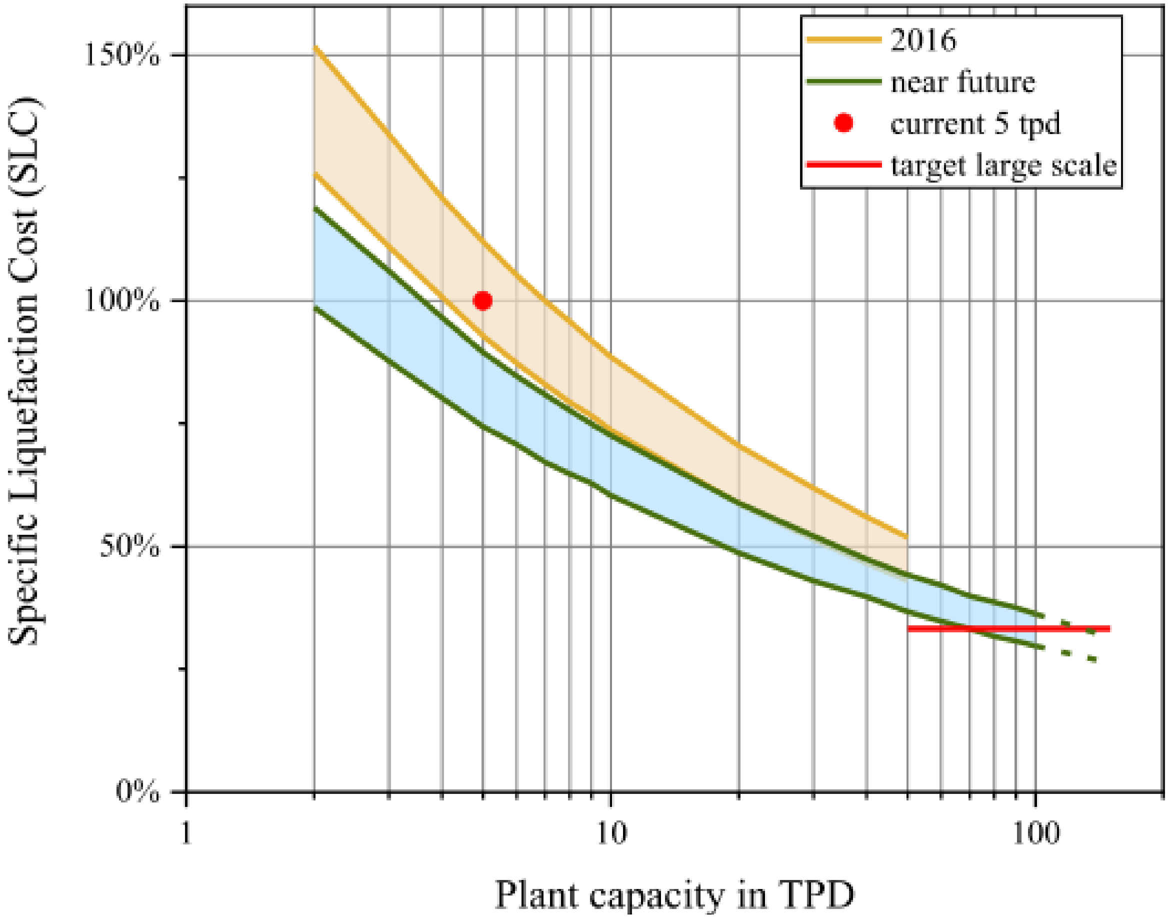
Items	Current		Short to medium term	Long term
Liquefaction capacity	<3 tons/day	<50 tons/day	up to 150 tons/day	≥100 tons/day
Main refrigeration cycle	Brayton	Claude	High-pressure Claude	High-pressure Claude
Refrigeration medium	Helium	Hydrogen	Hydrogen	Hydrogen
Precooling cycle	Liquid nitrogen	Liquid nitrogen	Liquid nitrogen or mixed refrigerant	Mixed refrigerant
Feed pressure	10–15 bar	15–20 bar	20–25 bar	>20 bar
Compressor type	Reciprocating	Reciprocating	Reciprocating	Centrifugal
Specific energy consumption	>12.3 kWh/kgLH$_2$	>10.8 kWh/kgLH$_2$	7.7–10.8 kWh/kgLH$_2$	<9 kWh/kgLH$_2$
Investment cost (CAPEX)	++	O	–	–
Operating cost (OPEX)	–	O	+	++
CAPEX & OPEX	–	O	+	++

o Neutral (+) Strength (-) Weakness

Zhang et al. (2023) Renewable and Sustainable Energy Reviews, 176, 113204

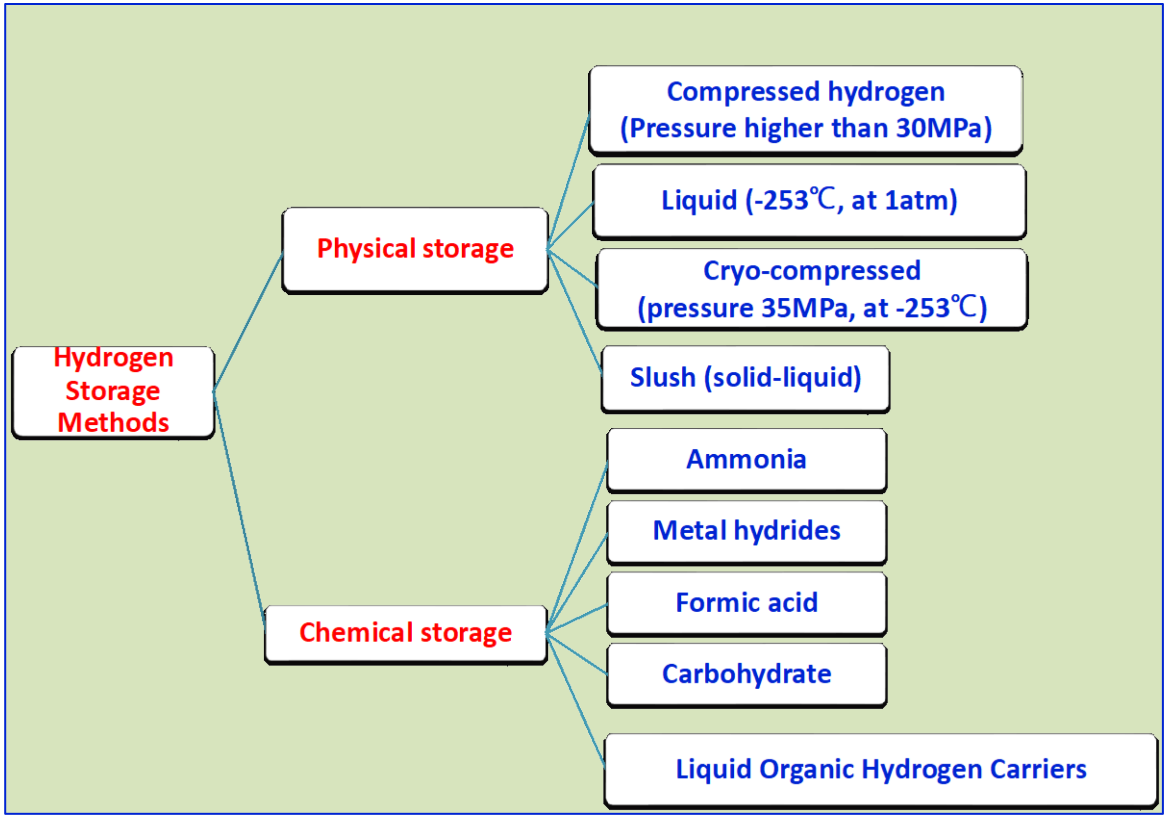
UNIVERSITY OF BIRMINGHAM

Projection of future costs of hydrogen liquefaction technologies



Cardella et al. (2017) International Journal of Hydrogen Energy. 2017;42:13329-38.

A summary of hydrogen storage methods / technologies: Classification



- Classification based on physics / chemistry

Zhang et al. (2023) Renewable and Sustainable Energy Reviews, 176, 113204

Comparison of characteristics of hydrogen storage methods / technologies

Storage medium state	Storage locations	Volume	Volumetric hydrogen storage density (g H_2/L)	Cycling	Geographical constraints
Gaseous state	Salt caverns	Large	~5-20 g/L (50-200 bar)	Weeks - Months	Limited
	Pressurized containers	Small	~40 g/L (700 bar)	Daily	Not limited
Liquid state	Liquid hydrogen containers	Small-medium	~66 g/L (1 bar)	Days - Weeks	Not limited
	Ammonia containers	Small to medium	107 g/L (1 bar)	Weeks - Months	Not limited
	LOHCs containers	Small to medium	55 g/L (benzyltoluene, 1 bar)	Weeks - Months	Not limited

Adapted from https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf (with modification in terms of scale of volume)

UNIVERSITY OF BIRMINGHAM

Comparison between liquid-phase hydrogen storage methods

Assessment indicators		Liquid hydrogen	LOHC (MCH)	Ammonia
Technology maturity [a]	Conversion	**Hydrogen liquefaction small scale: +** Hydrogen liquefaction large scale: -	Hydrogenation: O	**Haber-Bosch process: +**
	Reconversion	**Liquid hydrogen regasification: +**	De-hydrogenation: O	Ammonia cracking: O
	Tank storage	O→+	**+**	**+**
	Transport	Truck: + Ship: O→+	**Truck: +** **Ship: +**	**Truck: +** **Ship: +**
	Supply chain integration	O→+	O	**+**
Conversion and reconversion total energy consumption [b]		Current stage: 25-40% LHV_{H2} Potential: ~18% LHV_{H2}	Current stage: 35-40% LHV_{H2} Potential: 25% LHV_{H2}	Conversion: 7-18% LHV_{H2} Reconversion: <20% LHV_{H2}

[1] +: high technology maturity (proven and commercial), O: medium technology maturity (prototype demonstrated), -: low technology maturity (validated or under development); small scale: <5 tons/day, large scale: ≥100 tons/day.
[2] Given as a percentage of the lower heating value of hydrogen (values are for high-purity hydrogen that can be used in fuel cells).

Zhang et al. (2023) Renewable and Sustainable Energy Reviews, 176, 113204

Comparison between liquid-phase hydrogen storage methods

Assessment indicators		Liquid hydrogen	LOHC (MCH)	Ammonia
Technology maturity [a]	Conversion	Hydrogen liquefaction small scale: + **Hydrogen liquefaction large scale: -**	**Hydrogenation: O**	Haber-Bosch process: +
	Reconversion	Liquid hydrogen regasification: +	**De-hydrogenation: O**	**Ammonia cracking: O**
	Tank storage	O→+	+	+
	Transport	Truck: + Ship: O→+	Truck: + Ship: +	Truck: + Ship: +
	Supply chain integration	O→+	**O**	+
Conversion and reconversion total energy consumption [b]		Current stage: 25-40% LHV_{H2} Potential: ~18% LHV_{H2}	Current stage: 35-40% LHV_{H2} Potential: 25% LHV_{H2}	Conversion: 7-18% LHV_{H2} Reconversion: <20% LHV_{H2}

[1] +: high technology maturity (proven and commercial), O: medium technology maturity (prototype demonstrated), -: low technology maturity (validated or under development); small scale: <5 tons/day, large scale: ≥100 tons/day.
[2] Given as a percentage of the lower heating value of hydrogen (values are for high-purity hydrogen that can be used in fuel cells).

Zhang et al. (2023) Renewable and Sustainable Energy Reviews, 176, 113204

Comparison between liquid-phase hydrogen storage methods

Assessment indicators		Liquid hydrogen	LOHC (MCH)	Ammonia
Technology maturity [a]	Conversion	Hydrogen liquefaction small scale: + Hydrogen liquefaction large scale: -	Hydrogenation: O	Haber-Bosch process: +
	Reconversion	Liquid hydrogen regasification: +	De-hydrogenation: O	Ammonia cracking: O
	Tank storage	O→+	+	+
	Transport	Truck: + Ship: O→+	Truck: + Ship: +	Truck: + Ship: +
	Supply chain integration	O→+	O	+
Conversion and reconversion total energy consumption [b]		**Current stage: 25-40% LHV_{H2}** **Potential: ~18% LHV_{H2}**	**Current stage: 35-40% LHV_{H2}** **Potential: 25% LHV_{H2}**	**Conversion: 7-18% LHV_{H2}** **Reconversion: <20% LHV_{H2}**

[1] +: high technology maturity (proven and commercial), O: medium technology maturity (prototype demonstrated), -: low technology maturity (validated or under development); small scale: <5 tons/day, large scale: ≥100 tons/day.
[2] Given as a percentage of the lower heating value of hydrogen (values are for high-purity hydrogen that can be used in fuel cells).

Zhang et al. (2023) Renewable and Sustainable Energy Reviews, 176, 113204

UNIVERSITY OF BIRMINGHAM

Liquid hydrogen transportation

Transportation method	Transportation distance	Pressure	Hydrogen amount	Tank volume	BOG formation (per day)	Application examples or projections
Road	**Mid-range distance**	**≤ 7 bar**	**4 ton per truck**	**≤ 64 m^3**	**0.5 vol%**	**Air Products** transports liquid hydrogen via liquid semi- trailers with a capacity of 12,000 to 17,000 gallons (45-64 m^3).
Railway	**>1000 km**	**≤ 7 bar**	**7 ton per rail car**	**105 m^3**	**0.2 vol%**	**National Renewable Energy Laboratory** estimated that LH_2 rail delivery cost is likely to be lower than that of CGH_2 and LH_2 trucks/ pipelines delivery for long-distance and large-scale application.
Maritime	**Transoceanic delivery**	**≤7 bar**	**60 ton per tank**	**1,250-40,000 m^3**	**<0.2 vol%**	A pilot-scale liquid hydrogen supply chain **between Australia and Japan** (HySTRA Project, 1250 m^3 ship) has been completed in 2022.

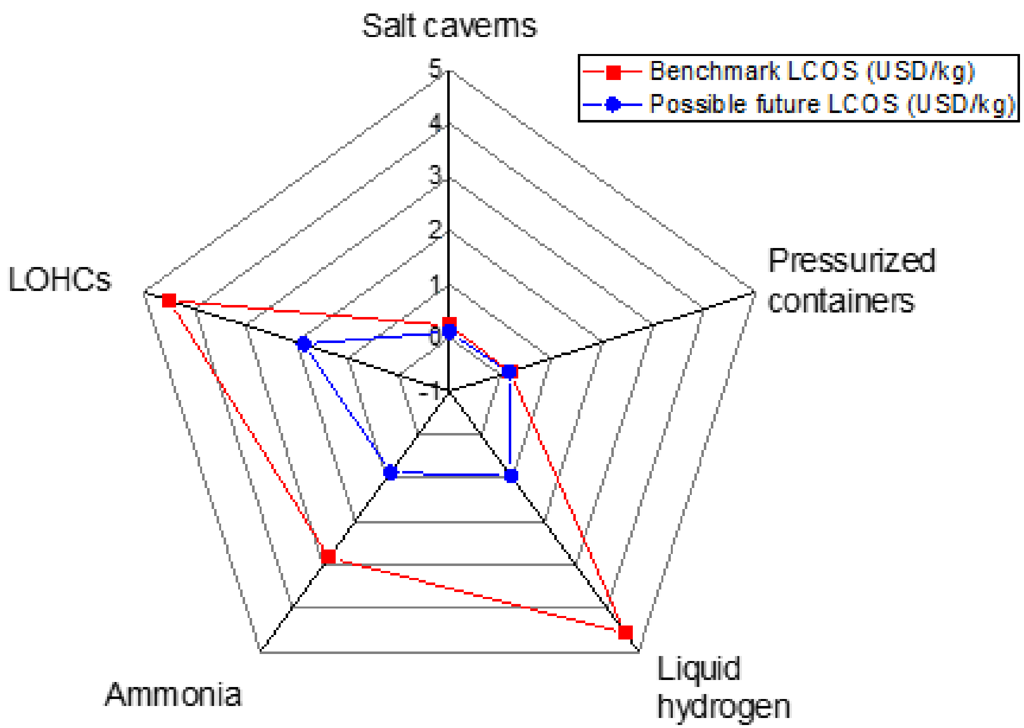
Contents

UNIVERSITY OF BIRMINGHAM

- Background
  - The role of hydrogen in future energy systems
  - The needs for liquid hydrogen
- Liquid hydrogen production, storage and transmission technologies and challenges
  - Hydrogen liquefaction
  - Liquid hydrogen storage
  - Liquid hydrogen transportation
- Economic aspects of liquid hydrogen
- Concluding remarks

Economic aspects of liquid hydrogen – storage costs

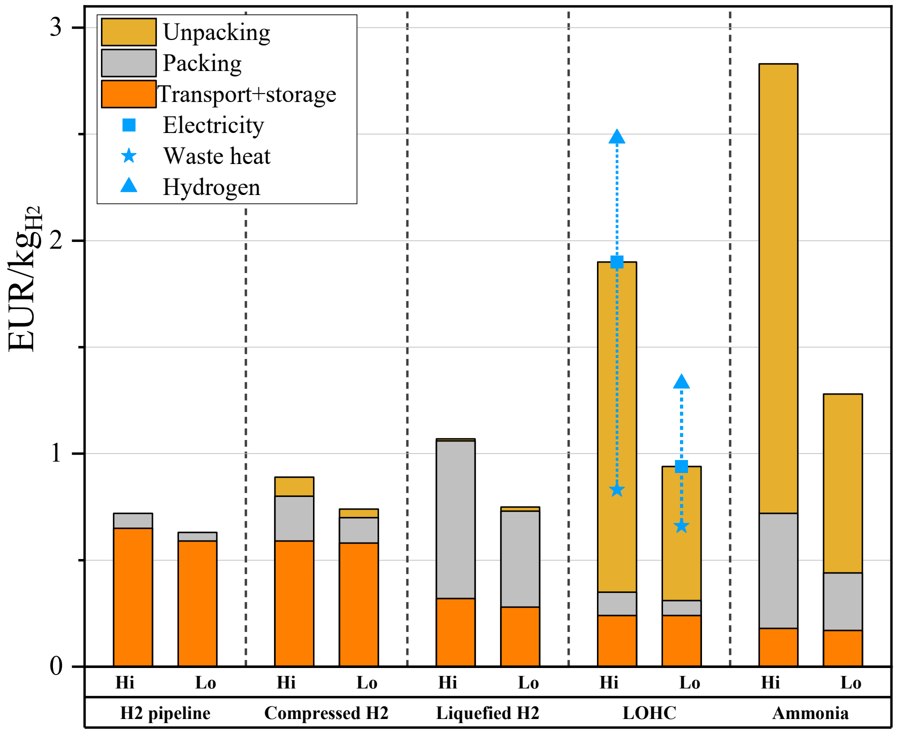
Current and projected future levelized cost of storage (LCOS) of different hydrogen storage methods



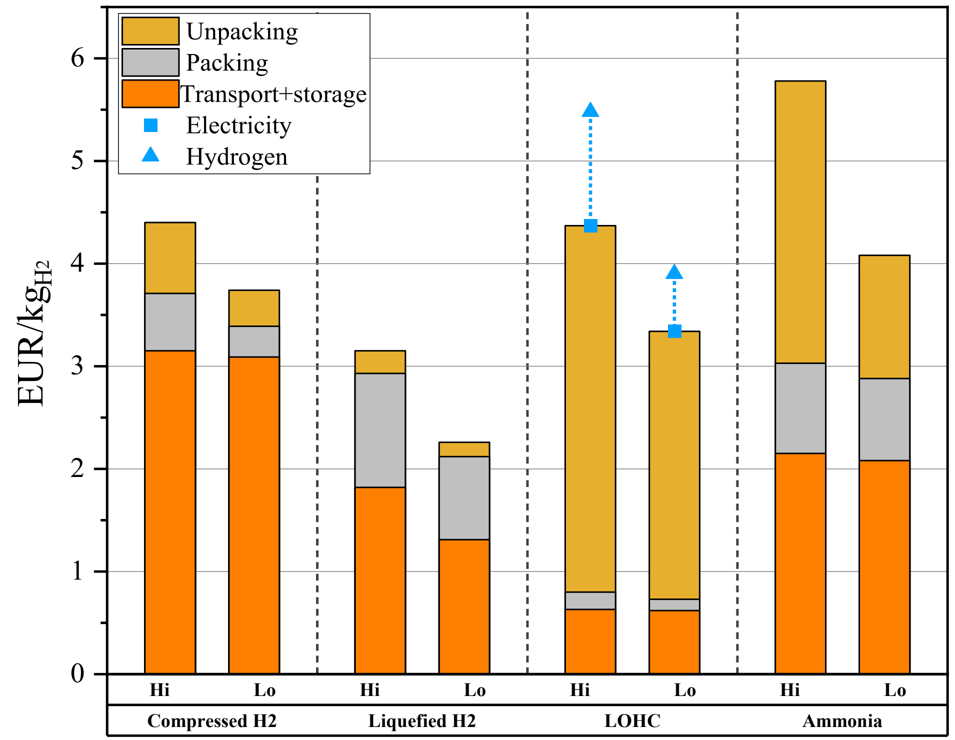
BloombersmallgNEF. Hydrogen Economy Outlook: Key messages. 2020.

Economic aspects of liquid hydrogen - long-distance transportation

Projected costs (2030-2035) of green hydrogen delivery with different storage methods for a transporting distance of 2500 km



Delivering green hydrogen to a single customer - 1 MtH_2 per year



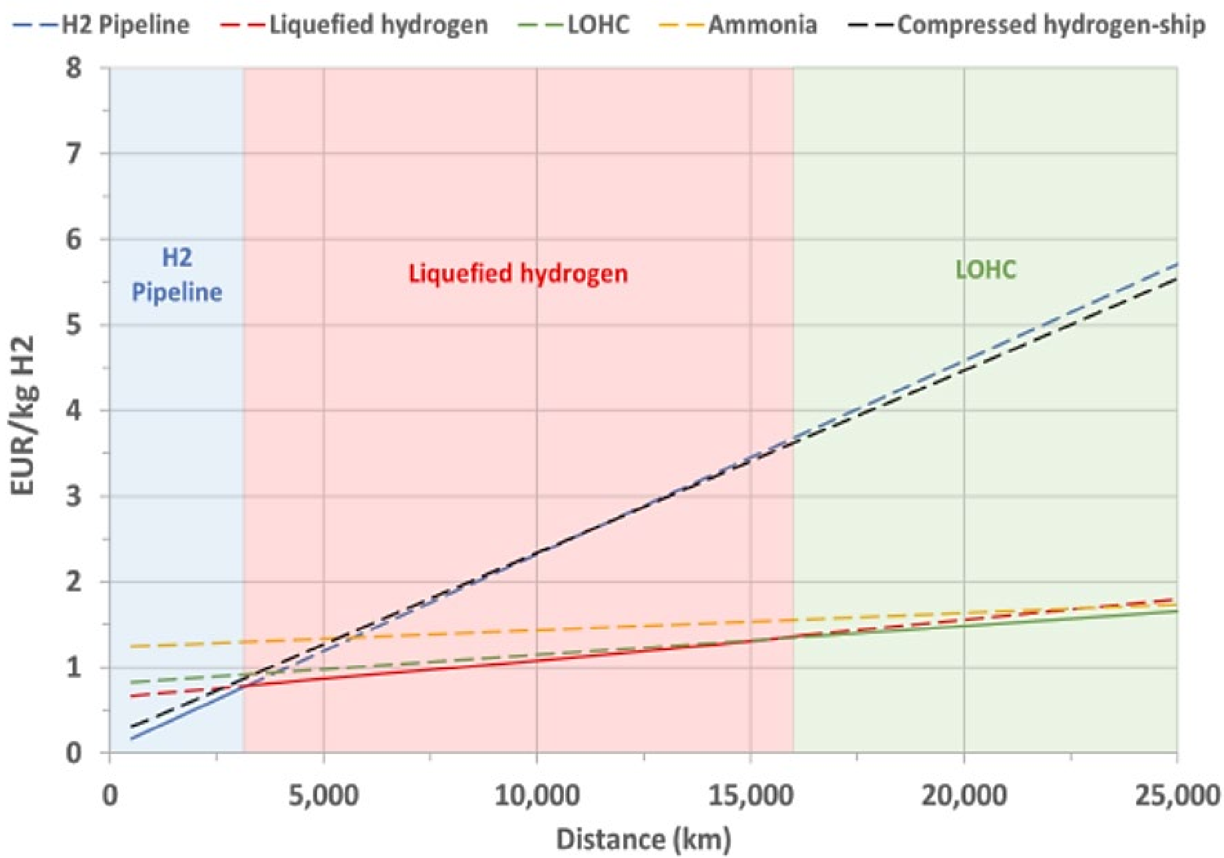
Delivering green hydrogen to a network of 270 hydrogen refuelling stations - 500 km distribution distance & 0.1 MtH_2 per year

Assessment of Hydrogen Delivery Options. The European Commission's science and knowledge service (joint research centre); 2021.

Economic aspects of liquid hydrogen - long-distance transportation

UNIVERSITY OF BIRMINGHAM

Projected costs (2030–2035) of clean hydrogen delivery for different storage methods vs transport distance in single end-user scenario (1 Mt/H_2 per year)



Liquid hydrogen provide an opportunity for long-distance energy transmission (e.g., intercontinental trade)

Assessment of Hydrogen Delivery Options. The European Commission's science and knowledge service (joint research centre); 2021.

Contents

UNIVERSITY OF BIRMINGHAM

- Background
  - The role of hydrogen in future energy systems
  - The needs for liquid hydrogen
- Liquid hydrogen production, storage and transmission technologies and challenges
  - Hydrogen liquefaction
  - Liquid hydrogen storage
  - Liquid hydrogen transportation
- Economic aspects of liquid hydrogen
- Concluding remarks

Concluding remarks

UNIVERSITY OF BIRMINGHAM

- Key factors limiting the use liquid hydrogen are high energy penalty due to high energy consumption of hydrogen liquefaction (>10 kWh/kgLH$_2$ on average) and high hydrogen boil-off losses during storage (1-5% per day). Solutions include:
  - Energy consumption: Innovative hydrogen liquefaction cycles and more efficient components, system scale and optimisation, which could lead to ~6 kWh/kgLH$_2$.
  - Hydrogen boil-off losses: Innovative design and optimisation of tank shape, structure, insulation and thermal management, as well as optimisation of supply chain, which could lead to a boiling rate below 1% vol, and even 0.1% vol per day.
- Liquid hydrogen could provide an opportunity as a key long-distance energy transmission method for distances ≥ 2000-3000 km due to cost advantages
- Countries with significant ship building industries could see an opportunity in developing liquid hydrogen based maritime transport

Thank you!

UNIVERSITY OF BIRMINGHAM

This paper is partially based on a collaborative review paper between University of Birmingham, UK, and Khalifa University, UAE [Zhang et al. (2023) Renewable and Sustainable Energy Reviews, 176, 113204]