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# Safely storing and moving Mega-Joules

## Safe aviation, road, rail, and maritime mobility using hydrogen fuel and safe transportation of hydrogen derivative cargoes in bulk

January 2024

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Note: for brevity, the focus of this presentation is green hydrogen from electrolysis and ammonia as a hydrogen derivative. Gasification, partial oxidation, reforming, pyrolysis and other blue / turquoise / grey hydrogen production techniques are not covered in detail. Neither are methanol and other hydrocarbon e-fuels as hydrogen derivatives. The hydrogen applications and use cases in this presentation focus on transportation and mobility, industrial applications of hydrogen are not in focus.

# Renewable electricity can decarbonise power generation and can electrify mobility and industrial processes. Direct electrification is efficient and can decarbonise many sectors.

Power and energy transition

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# The need for hydrogen as a clean energy vector to support renewable green electrons and as an essential chemical

Why suffer the losses of converting green electrons to hydrogen?

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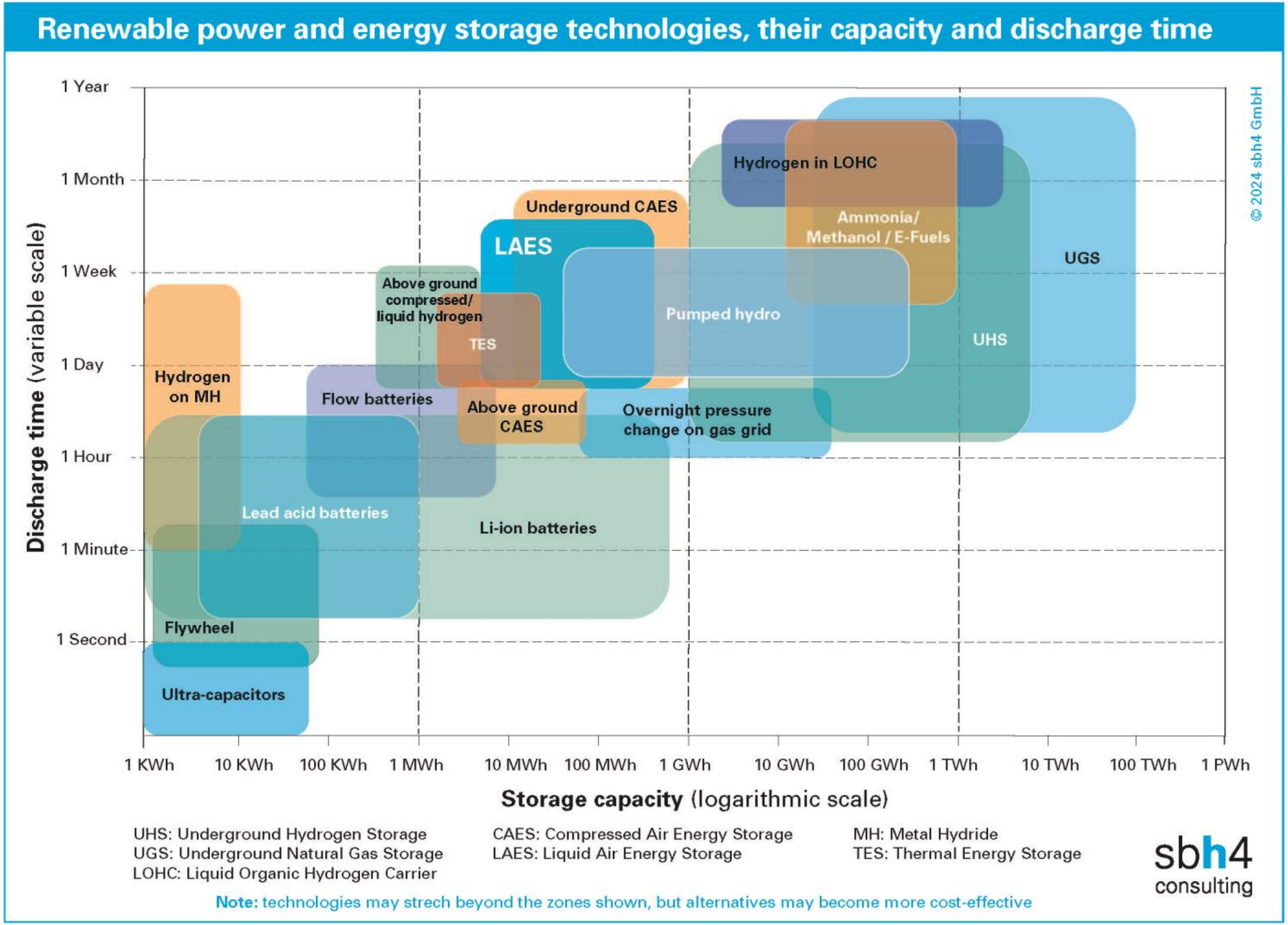


- Electricity is difficult to store over long periods in large quantities.
- Power to X (eg power to electrolysis to make hydrogen) can help balance variable renewables in the grid.
- Power to X can also store large quantities of energy for seasonal supply and demand balancing.

# Some processes and products rely on the chemical properties of hydrogen as a reducing agent or chemical feedstock. Vegetable oil hydration is required to produce HEFA bio-diesel and SAF. Hydrogen is also essential to make nitrogen fertilizers (ammonia, urea and ammonium nitrate).

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# Hydrogen as a safe molecule and addressing some common perceptions related to hydrogen safety

# Hydrogen can be dangerous and catastrophic events such as the Hindenberg stay in the public mind for a long time. However, examination of other airship incidents may lead to another conclusion: bulky airships were simply unsafe.

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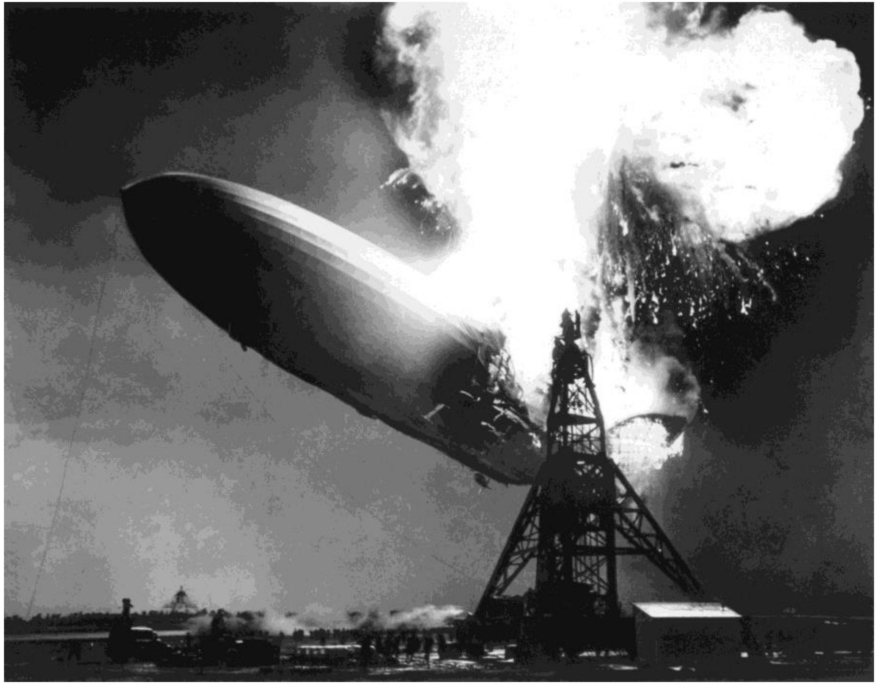


- The Hindenberg disaster in 1937 resulted in 35 members of crew and passengers losing their lives, out of the 97 people on board
- The helium-filled USS Akron crashed because of a thunderstorm in 1933, all 73 crew and passengers on board were killed

# Will fear and negative public perception be the weak links in hydrogen adoption?

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# Hydrogen is a 'new', 'unknown' fuel. Public perception has not yet become 'desensitized' to the risks – as when handling gasoline or diesel.


# A simplified view of hazards of various fuels: CLP Hazard identification pictograms

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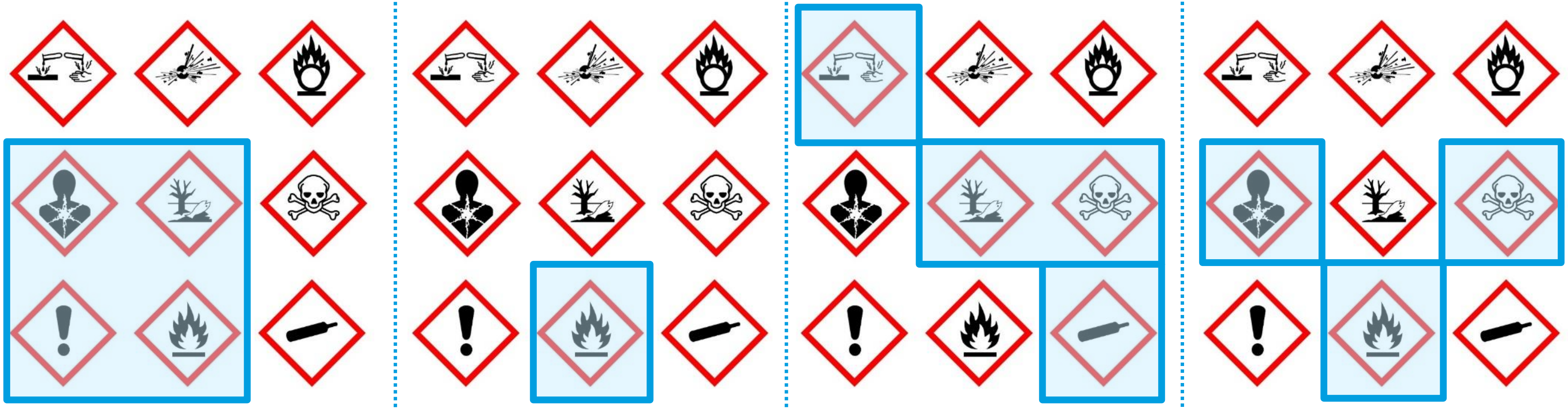
Unleaded Petrol E95 | LPG (Barbeque gas) | Ammonia | Methanol

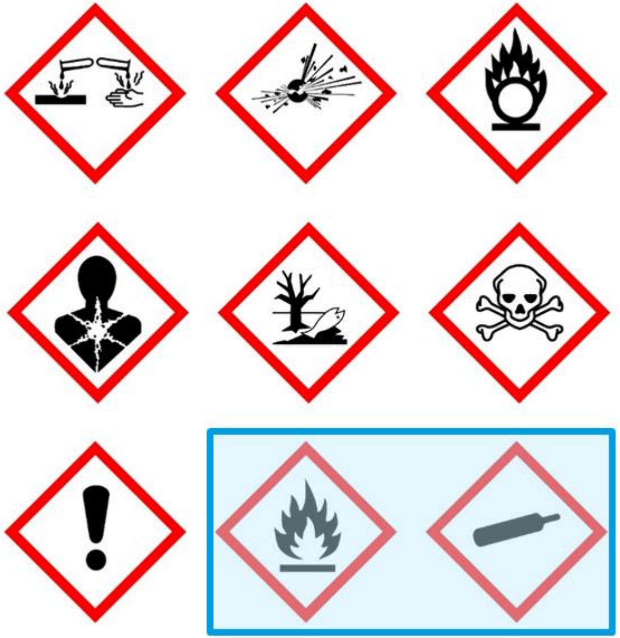


# Diesel and battery buses also suffer from fires. All fuels are used for their high energy value… there are inherent risks.



https://www.gazetteandherald.co.uk/news/11180454.stagecoach-confirms-inquiry-to-take-place-into-marlborough-high-street-bus-fire/
https://www.sustainable-bus.com/news/bus-fire-paris-ratp/
https://www.linkedin.com/posts/jmariocotzaceo_imagine-your-electric-car-battery-catching-activity-7050154170309328896-nEYL?utm_source=share&utm_medium=member_desktop

## Compressed hydrogen gas, liquid hydrogen, compressed natural gas (CNG) & LNG all carry the same CLP Hazard identification pictograms. CNG is also a high-pressure flammable gas on vehicles. Similar precautions are taken for CNG and hydrogen.



https://www.autoblog.com/2022/04/21/cng-bus-fire-explosion-italy-natural-gas/

# Hydrogen mobility can learn from 1.3 million CNG vehicles and 2,700 CNG stations in Europe.

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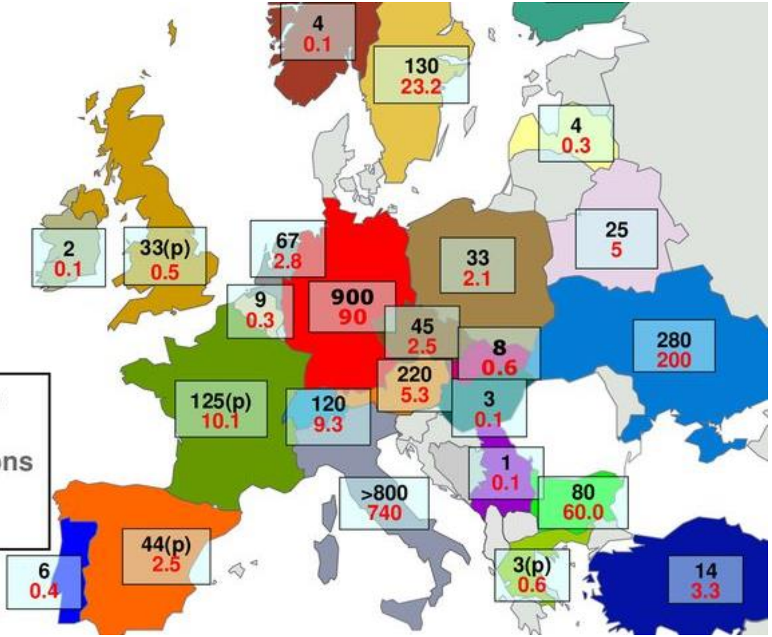
https://h2.live/en/

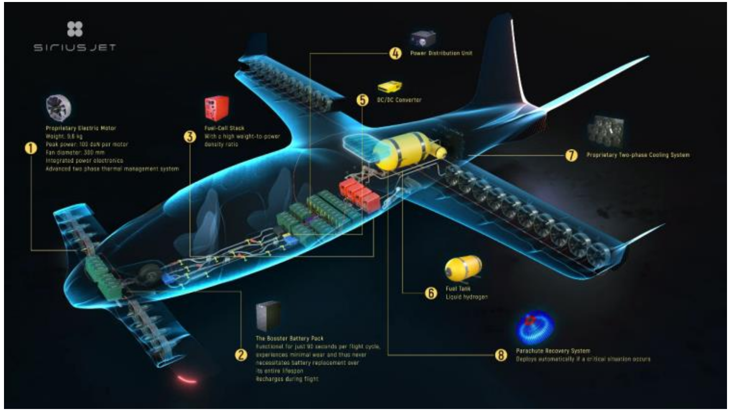
Total NGV in Europe: 1.3 million
Total refuelling stations in Europe: 2,700




Source: ENI
https://slideplayer.com/slide/14367111/

# Hydrogen has been used for rocket propulsion for decades. Hydrogen may also emerge as a fuel for aviation.

- The high gravimetric energy density of hydrogen makes it suitable as an aviation fuel, where weight is critical.
- Vertical take-off (VTOL) and vertical space rocket launches are extremely sensitive to weight.
- Hydrogen-powered drones are in service for: fertiliser dosing, chemical plant maintenance and pipeline monitoring. They may scale up and penetrate a wider range of applications, for example packet deliveries and urban taxis.
- Hydrogen fuelled, fuel-cell powered turbo-prop aircraft have been tested in the UK, USA, Germany, Switzerland and China by companies such as Ruixiang, H2FLY, HES Energy Systems, Sirius Jet, ZeroAvia and Pipistrel. Gaseous or liquid hydrogen may be used as a fuel for these lighter aircraft.
- Airbus is developing a range of ZEROe hydrogen fuelled aircraft, including jet aircraft.
- The weight of the hydrogen storage vessel must be considered in addition to the weight of hydrogen.
- Type 4 carbon fibre composite cylinders at 700 bar or more will be favoured if compressed gas is used.
- Liquid hydrogen will be required as a fuel for larger jet aircraft that will serve longer routes at higher speeds.
- Composite storage tanks for liquid hydrogen are being developed.




https://newatlas.com/aircraft/sirius-jet-hydrogen-vtol/#gallery:1/
VTOL aircraft from Sirius Aviation AG

https://www.electrive.net/2020/09/30/h2-flugzeug-von-zeroavia-gelingt-erstflug/

https://www.h2-view.com/story/doosan-mobility-hydrogen-drones-enter-the-european-market/


https://www.airbus.com/innovation/zero-emission/hydrogen/zeroe.html


Liquid hydrogen storage at Cape Canaveral

# Easyjet and Rolls Royce have tested a hydrogen fired AE 2100-A regional jet engine.

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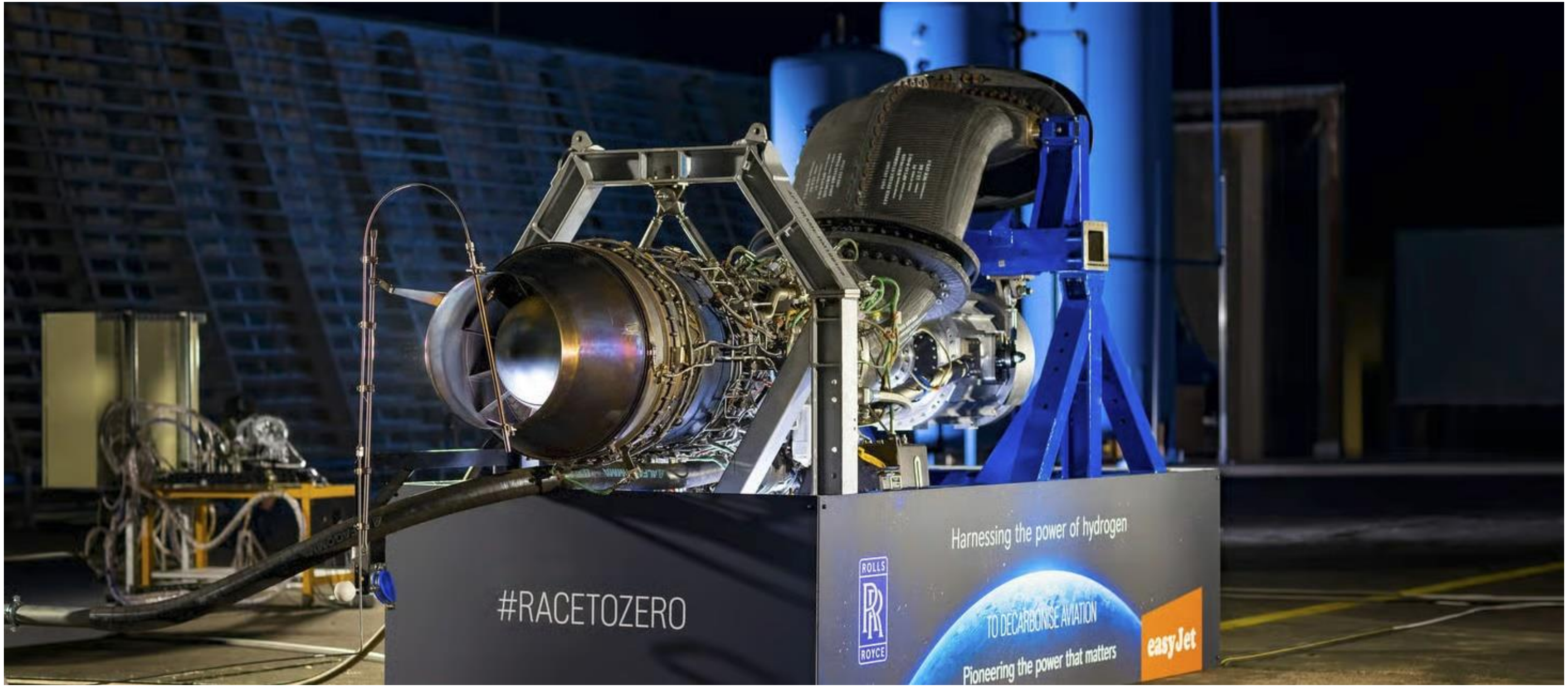


https://www.h2-view.com/story/rolls-royce-and-easyjet-complete-worlds-first-jet-engine-test-run-on-hydrogen/?utm_source=dlvr.it&utm_medium=linkedin&utm_campaign=rss

# Universal hydrogen is developing refillable liquid hydrogen modules, and a full liquid hydrogen supply chain for fuel-cell powered regional turbo prop flight.

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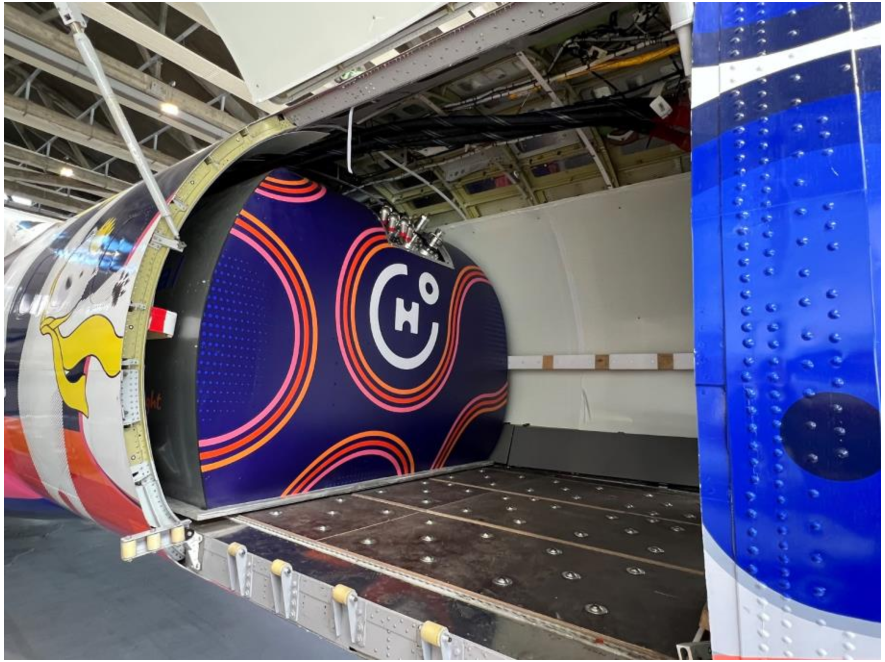

Hydrogen fuel cell powered ferries are being used in maritime applications for shorter routes. Compressed or liquid hydrogen is stored on the vessels. CMB.TECH uses hydrogen blended with diesel as a dual fuel in modified internal combustion engines on the Hydrotug 1, which operates in the Port of Antwerp-Bruges.

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Hydra hydrogen powered ferry, Norway


Sea Change hydrogen powered ferry, California

# 6x multi-cylinder bundles of high pressure compressed hydrogen gas cylinders on the fore-deck store hydrogen. Note the safety equipment used during the refilling operation.

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https://cdn.uc.assets.prezly.com/5036ebaa-f9df-495e-b449-6bca0a998d67/Belgaimage-82165088.jpg
https://www.thenationalnews.com/world/2023/12/13/belgian-port-has-high-climate-hopes-for-test-hydrogen-tugboat/

# CMB.TECH uses hydrogen blended with diesel as a dual fuel in modified internal combustion engines on the Hydrocat 48, a wind farm crew transfer vessel. Refuelling can be from a mobile system on a hydrogen road trailer.

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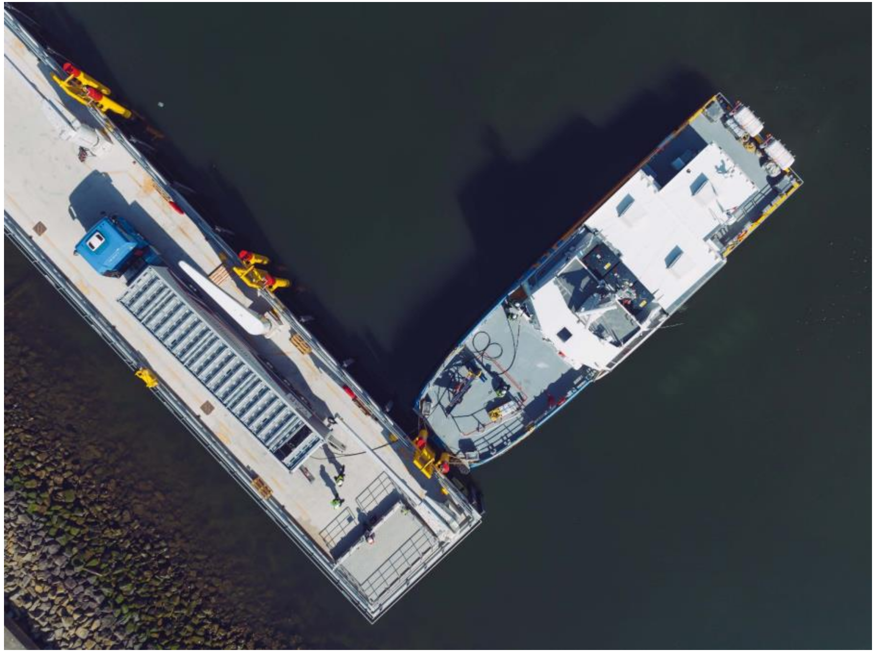

# KEYOU – Duetz pure hydrogen fired internal combustion engine in 18 tonne Daimler Truck. Engine / vehicle retrofits may be possible in the future. Hydrogen storage at 350 bar for local operation with >500 km range.

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https://www.keyou.de/press-release-world-premiere-keyou-presents-18t-truck-and-12m-city-bus-with-hydrogen-engine-for-the-first-time/?lang=en

# Type 3 and type 4 cylinders are converging to 700 bar for compressed hydrogen gas storage on long haul trucks. 700 bar has been used for hydrogen storage in cars for several years.

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# Compressed hydrogen gas storage in passenger cars is generally at 700 bar due to space limitations. For cars at 350 or 700 bar, J2601_202005 is relevant: Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles.

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# Hydrogen fuel cell powered trains and buses. Compressed hydrogen gas storage for mass-transit passenger vehicles is generally at 350 bar. For buses and 350 bar refuelling, J2601/2_202307 is relevant 'Fueling Protocol for Gaseous Hydrogen Powered Heavy Duty Vehicles'.

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- Hydrogen storage on trains and buses and trucks is generally in large type 3 or type 4 compressed hydrogen gas cylinders that operate at a pressure of 350 bar
  - Automotive hydrogen storage is generally in small tanks at 700 bar due to space restrictions
  - Trucks are migrating to 700 bar
  - Liquid storage on trucks has also been promoted by some OEMs, such as Daimler
- Hydrogen pressure is reduced from 350 bar to 10 bar and piped from the tank to the fuel cell
- The hydrogen storage system is fitted with automatic shut off valves and other safety devices to limit hydrogen emissions in the event of a vehicle crash




https://fuelcellsworks.com/news/worlds-first-hydrogen-train-with-a-speed-of-160-kilometers-per-hour-rolled-out-in-china/

## Hydrogen fired internal combustion engines are being developed for medium duty on-road and off-road applications. A lower purity (lower cost) of hydrogen can be used since the ICE is more tolerant of Sulphur, N2 and CO impurities in the H2 than fuel cells are. ISO 14687:2019, Hydrogen fuel quality Product specification is relevant and has different purity grades.

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- JCB has built and is testing 50 hydrogen fired internal combustion engines
- Targeted for off-road construction machines (backhoe loader and Loadall telescopic handler) and agricultural machinery
- JCB has also retrofitted their hydrogen fired internal combustion engine into a 7.5 tonne Mercedes truck


# Beyond JCB, offroad hydrogen mobility is also on the way in for several applications.

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Fendt, Germany - hydrogen fuel cell powered tractor, H2ARGAR research project


Ski piste grooming machine, Austria


Fork-lift truck and refueller



https://www.fendt.com/int/geneva-assets/widget/37559/news-2-high.jpg

# FCEV hydrogen storage tank testing. Vibration tests and permeation tests.

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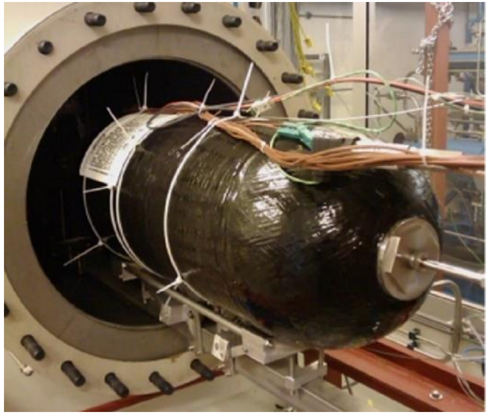
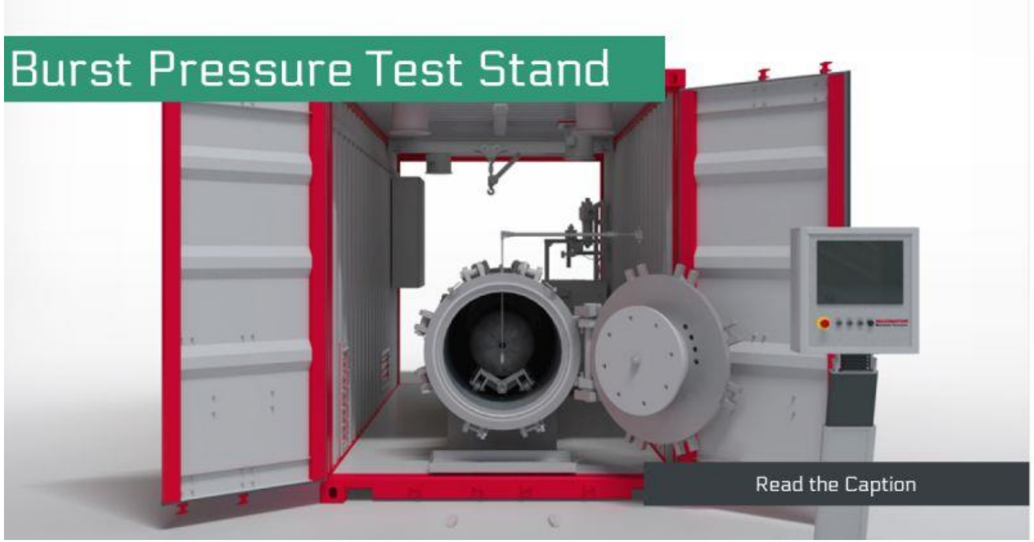
- The robustness of high-pressure hydrogen type 4 carbon fibre composite gas storage cylinders for mobility applications is rigorously tested
- The intent is to prove that the cylinder has been designed and manufactured so that it will not rupture in service
- The testing is intended to reduce the **frequency** of a catastrophic failure by validating the design basis and the manufacturing process



- The permeation rate (gas leakage through the walls and other connections of the cylinder) is also tested
- The intent is to prove that the cylinder has been designed and manufactured so that it will not release any hydrogen gas when in service
- The testing is intended to reduce the **severity** of a hydrogen gas leak and avoid hydrogen gas build up and thereby avoid a flammable atmosphere being created, eg in a confined space (car garage) whilst the car is parked for a long duration (eg one month)

# High-pressure type 3 and type 4, carbon fibre wrapped composite gas cylinder burst test equipment. Burst tests at up to 2,400 bar are required for new cylinder design type-testing and occasional production batch tests.




https://www.linkedin.com/posts/steelhead-composites_hydrogen-composite-activity-7151280598798471168-Asxr/?utm_source=share&utm_medium=member_ios

https://www.linkedin.com/feed/update/urn:li:activity:7151480146816827392/?utm_source=share&utm_medium=member_ios

# An exploding hydrogen storage tank in an FCEV could be fatal for the vehicle occupants. Conclusion: better to vent the hydrogen if the pressure builds up than let the tank explode.

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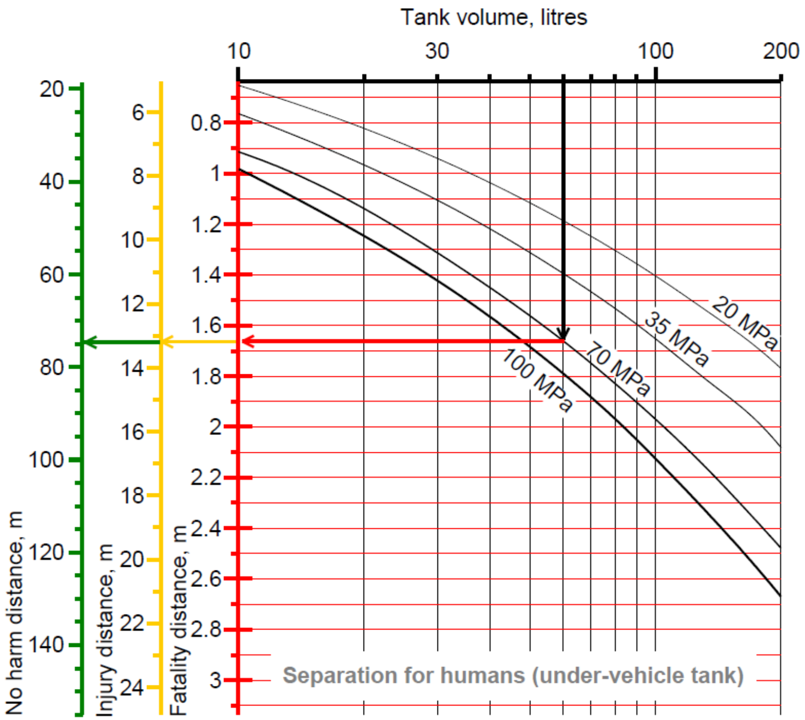


## Test conditions

- 60 litre volume (water capacity) hydrogen tank
- Operating pressure 700 bar
- Mounted under a hydrogen powered vehicle

## Conclusions

- Safe distance for humans circa 70m
- Injury distance circa 13m
- Fatal distance circa 1.7m

# Thermal Pressure Relief Device (TPRD) for use in the event of a fire. Generally, uses a glass bulb manufactured to burst at circa 110 °C. Hydrogen release can be highly directional – away from the vehicle occupants.

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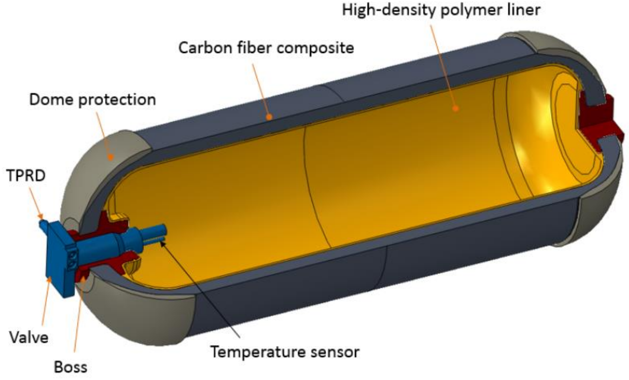
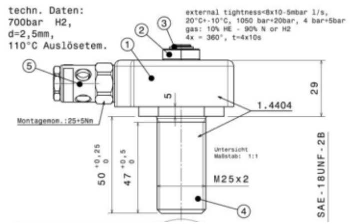



TPRD = Thermally Activated Pressure Relief Device

**Thermal pressure Relief Device Orientable**
Working Pressure PN 350 / 700
Material: Stainless steel 1.4404 / 316 L
Connections: M 25 x 2 or 11/8" UNF MALE
Temperature of Gls bulb: 110° C
Canalisable vent connection: 9/16" SAE -18UNF-2B
Flow passage d = 2,5 mm
Weight : ~1,8 kg




https://www.energy.gov/eere/fuelcells/physical-hydrogen-storage
https://phys.org/news/2009-08-solar-hydrogen-economy-world-energy.html
https://www.europages.co.uk/TPRD-EndPlug/PTEC-PRESSURE-TECHNOLOGY-GMBH/cpid-5188551.html
https://www.h2-tech.nl/site/assets/files/1436/tprd_h2_datasheet.pdf

# Periodic pressure testing of high-pressure type 1 solid steel hydrogen gas cylinders is essential.

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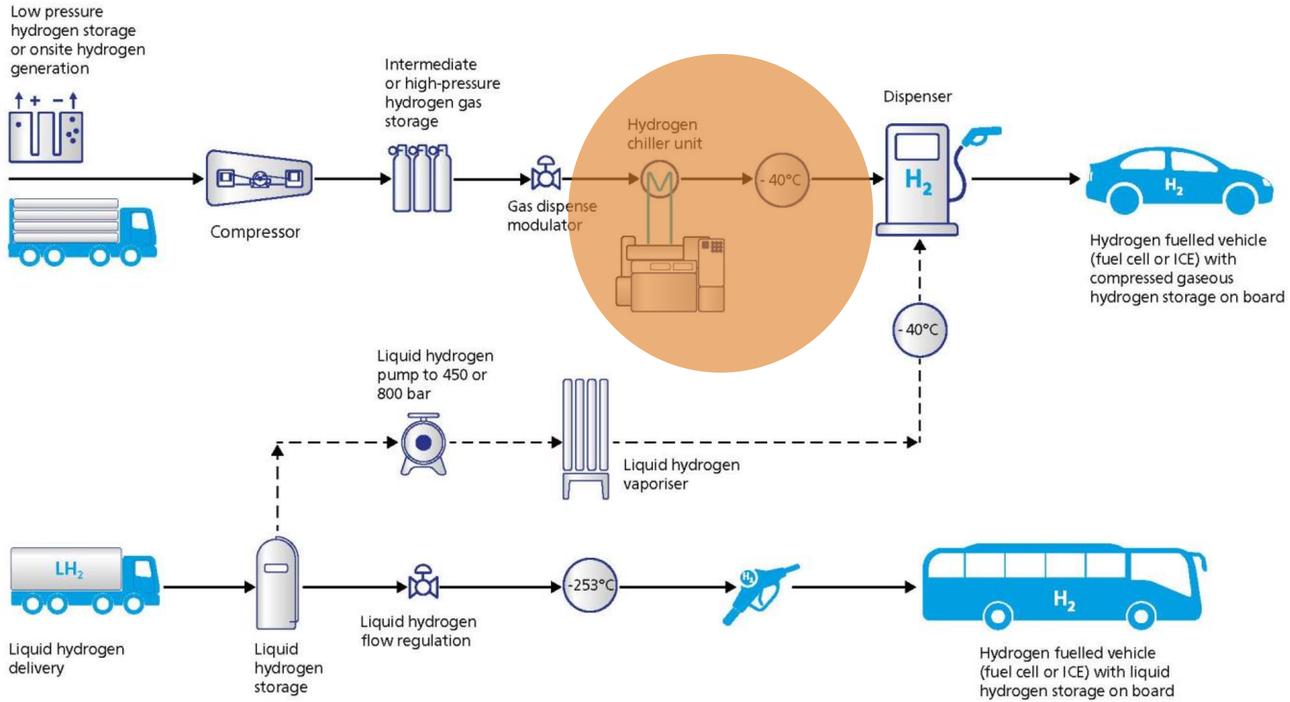
- Progressive hydrogen embrittlement of the steel can reduce the tensile strength over an extended period of operation
- Periodic pressure testing the robustness of a type 1 steel high pressure hydrogen gas storage cylinder for hydrogen static storage or distribution applications
- The intent is to prove that the cylinder is still of a high integrity after a period of service so that it will not rupture during the next period of service

# Compressed Gas, Liquid Hydrogen and Multi-Modal Hydrogen Refuelling Station Layouts

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- Pre-chilling of the compressed hydrogen gas is required prior to decant into the vehicle to avoid over-heating the FCEV storage tank.
- The SAE Protocols (J2601 series) allow for different temperatures: T40 (-40 °C), T30 (-30 °C) and T20 (-20 °C).
- T10 (-10 °C) and ambient Protocols may be developed in the future.

# Joule-Thomson Effect for Heating and Cooling of Gases as They Expand

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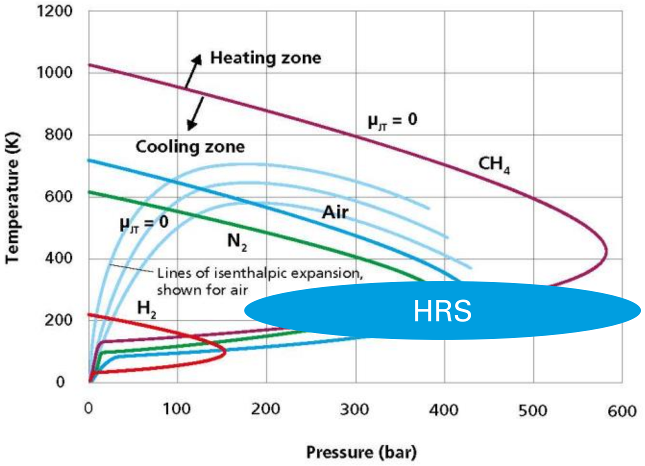
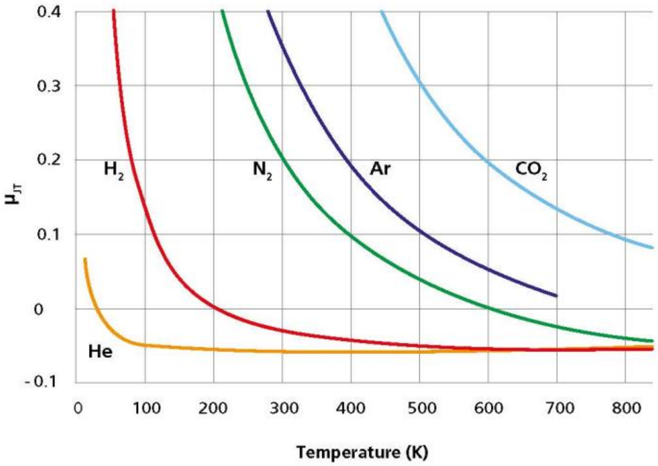
Joule-Thomson Inversion Curve




$H_2$ Hydrogen
$N_2$ Nitrogen
$CH_4$ Methane
He Helium
Ar Argon
$CO_2$ Carbon dioxide

$\mu_{JT}$ – Joule-Thomson coefficient (K/bar) and inversion temperatures at atmospheric pressure




$\mu_{JT} > 0$ means the gas will cool down during expansion
$\mu_{JT} < 0$ means the gas will warm up during expansion

- Expansion of hydrogen from high pressure at ambient temperature results in heat generation and a temperature increase

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# High-pressure hydrogen gas compression for HRS hydrogen storage applications can operate at up to 950 bar. Containerised applications are ideal for fixed gas detection using chemical sensors to identify hydrogen gas leaks.

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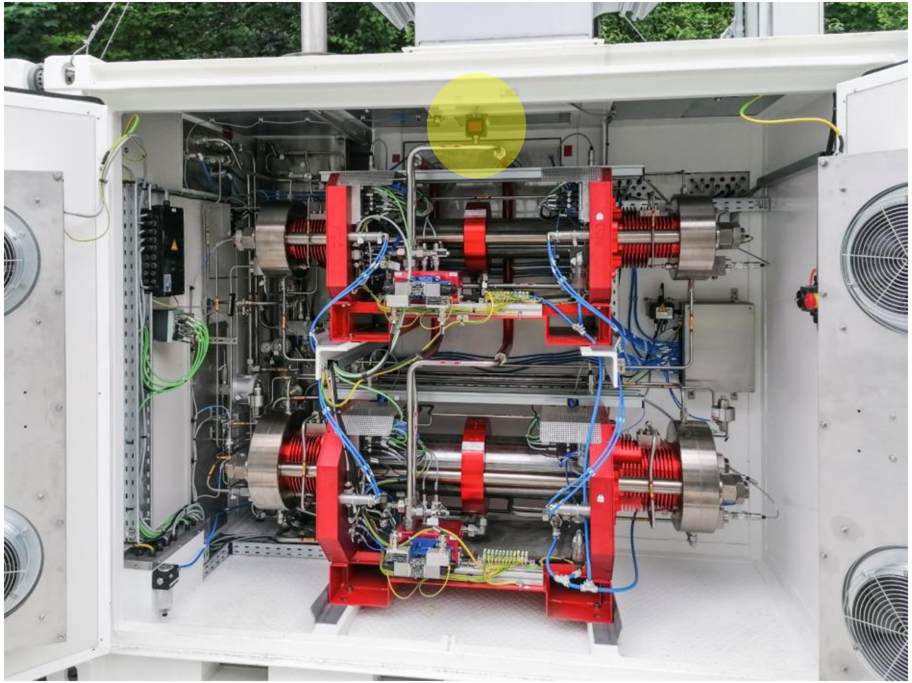

- Hydrogen gas compressors can achieve 940 bar pressure for hydrogen refuelling stations
- The compressor fills high pressure buffer storage tanks ready for the arrival of a vehicle that requires refuelling
- The containerised, enclosed compressor system requires gas detection and good ventilation to avoid hydrogen build up in case of a gas leak
- Ventilation can be increased if a hydrogen gas leak is detected
- The confined space (no external wind) is ideal for fixed gas detection equipment
- Since it is a contained system (no ambient wind) a low-cost pellistor type LEL gas detection sensor can be used
- Electrical items, eg control circuits and instrumentation within the cabinet can be Ex rated so that they do not create sparks and do not over-heat and thus avoid a potential ignition source

# Hydrogen burns with an inorganic flame. Flame detection can be more suitable than chemical sensor-based gas detection in outdoor spaces where hydrogen is stored due to the possibility that wind blows a hydrogen gas leak away from chemical sensor gas detection equipment. Specialised flame detection equipment for hydrogen must be used.

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Hydrocarbon flame detection system


Hydrogen flame detection system

- Combustion of hydrogen produces only water vapour and heat, not soot and $CO_2$
- Conventional flame detection as used with hydrocarbon flames is not possible for hydrogen.
- Special flame detection equipment is required which is suited to the nature of a hydrogen flame.
- In addition to gas and flame detection, avoidance of gas leaks with high quality equipment and good maintenance procedures is essential.

Fixed chemical sensor gas detector

# In outdoor open spaces, ultrasound leak detection for hydrogen can be more reliable than chemical sensor-based gas detection because wind can blow the hydrogen gas leak away from the chemical sensor. Portable ultrasound detection can also be used to pinpoint leaks for maintenance.

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https://www.uesystems.com/en-gb/product/ultraprobe-15000/
https://www.offshore-technology.com/contractors/fire_protection/innova/

# Liquid hydrogen on the HRS can be used to supply liquid or gas to the vehicle. Some hazards of liquid hydrogen are different to compressed hydrogen gas.

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- Hydrogen would be delivered to the HRS site as a bulk liquid and pumped into the liquid hydrogen storage tanks on the vehicle.
- These stations may be dual-fuel, where the liquid hydrogen can be vaporised to fill high pressure gaseous hydrogen into vehicles at 350 bar or 700 bar.
- To create liquid hydrogen, almost two times more electrical power is required than for high pressure hydrogen gas compression, but the power is required at the producer location, not the HRS location.
- For the HRS operator, pumping liquid hydrogen to pressure then vaporisation consumes less power than compression of the hydrogen.
- One motivation for using liquid hydrogen is the higher volumetric energy density compared to high pressure gaseous hydrogen. This benefit is felt all through the supply chain in bulk distribution, static storage at the HRS and on-board storage on the FCEV.
- Pumping liquid means faster refuelling times – a major benefit for high duty cycle operation, eg long distance trucking.
- The quantities of liquid hydrogen stored at the HRS may be in the order of 10 tonnes, circa 10x more than at a gaseous hydrogen fuelling station.
- Cryogenic hazards (cold temperature, embrittlement, vapour expansion) must also be considered.



https://www.chartindustries.com/Products/Hydrogen-Fueling-Stations
https://www.chartindustries.com/Products/Hydrogen-Energy
https://www.stantec.com/en/ideas/topic/mobility/webinar-recording-demystifying-hydrogen-fueling-for-transit-fleets

# Pressure relief systems are required to vent expanding cryogenic vapours if liquid hydrogen has become trapped in a closed system.

# To avoid the problem of cryogenic embrittlement, copper, some austenitic stainless steels and some aluminium alloys can withstand the super-cold cryogenic temperature of liquid hydrogen, -253 °C.

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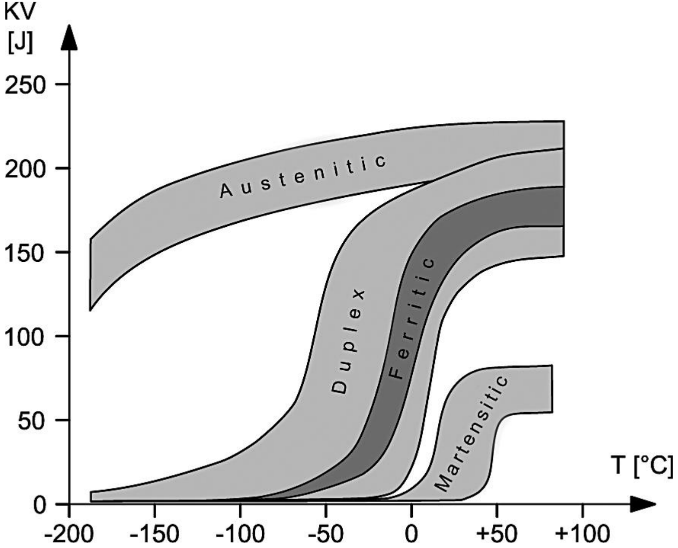





https://www.ejournals.eu/pliki/art/5743/

# PPE for use when working with cryogenic liquid hydrogen may be required. PPE is important but it should be the last line of defence.

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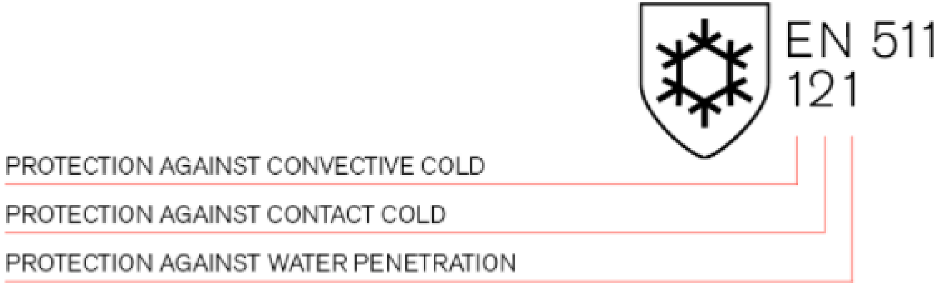




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# The safety of hydrogen production on electrolysers

# ISO 22734 specifies gas detection requirements for hydrogen electrolysers and control functions that should result if a gas leak is detected. In containerised and indoor electrolysers, chemical hydrogen gas detection sensors (eg pellistor LEL or electrochemical sensor) are suitable.

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**4.4.1.4 Protection methods to prevent the accumulation of ignitable mixtures**

Protection may be provided by passive or active means to ensure that gas mixtures remain below a volume fraction of 1 % hydrogen in air within the enclosure, except in dilution volumes. Computational fluid dynamics analysis, tracer gas, or similar methods such as those given in IEC 60079-10-1, may be used to determine the 1 % volume fraction of hydrogen in air dilution boundary and ventilation requirements.

NOTE Refer to Annex B.

Passive methods include, but are not limited to:

a) pipe orifices and similar methods of flow restriction to restrict the maximum release rate to a predictable value,

b) use of joints that are permanently secured and constructed so that they limit the maximum release rate to a predictable value, and

c) natural ventilation.

Active methods include, but are not limited to:

d) comparison of hydrogen gas flow or pressure measurements relative to control settings to initiate protective measures such as de-energization of non-classified electrical equipment and initiation of ventilation when an out-of-specification condition is detected,

e) constant ventilation sufficient to maintain an average hydrogen gas concentration within the enclosure, except in dilution volumes, below the maximum volume fraction of 1 % hydrogen based on the maximum anticipated hydrogen gas leak rate into the enclosure as determined by the manufacturer,

f) a hydrogen gas detection system complying with the requirements of 4.4.1.9 that initiates ventilation at an appropriate volume fraction less than 1 % hydrogen.

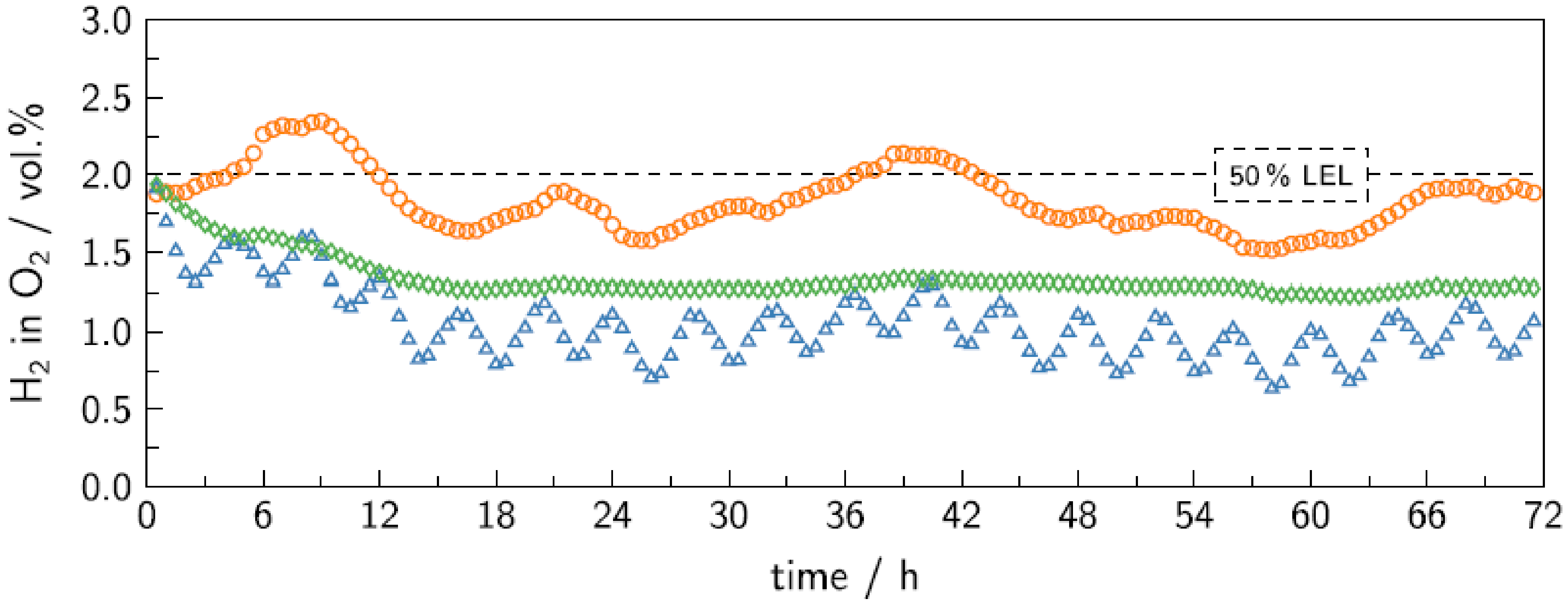
INTERNATIONAL STANDARD **ISO 22734** **Hydrogen generators using water electrolysis — Industrial, commercial, and residential applications**

# Multiple gas detectors: hydrogen leak detection with multiple gas detection sensors; simultaneous oxygen and hydrogen leak detection.

Image credit Shaanxi Westitan

- Different gas detection sensor technologies are used to detect different gases present in the electrolyser system, ie oxygen and hydrogen
- For detecting the same gas it is possible to use two different sensor technologies in parallel
- ‘Doubling up‘ with different technologies makes the system more robust, for example to exposure to saturation events or gases that are harmful to one sensor technology
- ‘Doubling up‘ across multiple technologies can also cover a wider range of measurement

# For alkaline electrolysis, the hydrogen in oxygen concentration can be 1.5%. 2% would be 50% of the LEL. For safety management and electrolyser process control, a measurement range of 0 to 5% may be suitable.






Experimental evaluation of dynamic operating concepts for alkaline water electrolyzers powered by renewable energy, Jörn Brauns & Thomas Tuerk in Alectrochimica Acta, Dec 2021

# Cockerill Jingli, Longi and Peric alkaline electrolysers at the world's largest electrolyser park (260MW, Sinopec Kuqa, China) cannot operate below 50% of name plate capacity, despite performance claims of turndown to 30%. Hydrogen gas carry over into the oxygen due to use of low-cost diaphragm materials is the issue.

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https://www.hydrogeninsight.com/production/exclusive-worlds-largest-green-hydrogen-project-has-major-problems-due-to-its-chinese-electrolysers-bnef/2-1-1566679
https://www.scmp.com/business/article/3247148/chinas-sinopec-says-world-leading-green-hydrogen-project-will-take-longer-expected-ramp

# Gas analysis equipment for process control inside a McPhy containerised alkaline electrolyser.

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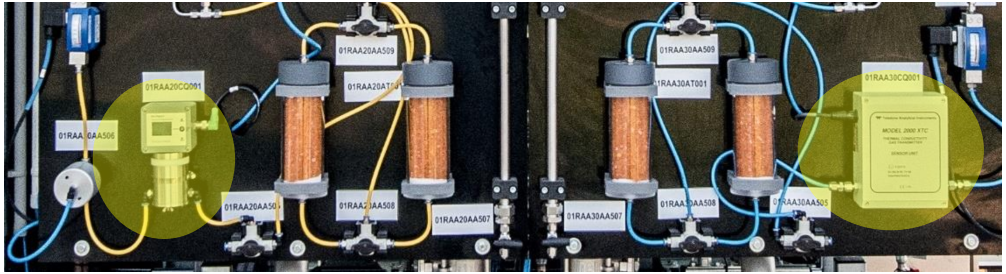
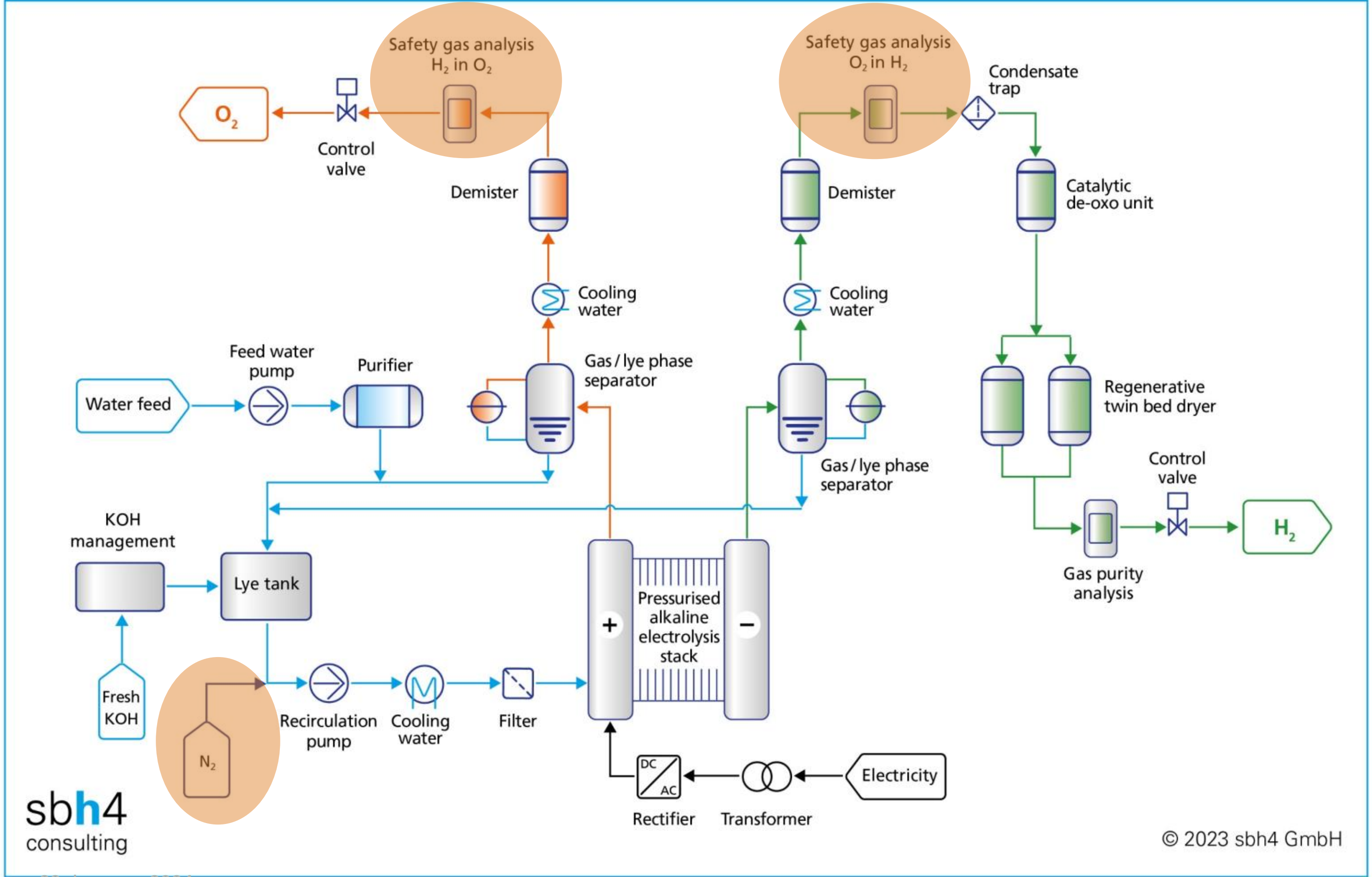



- An electrochemical cell oxygen analyser is used to detect high levels of oxygen in the “pure“ hydrogen product gas
- A TCD hydrogen analyser is used to detect undesirable high levels of hydrogen in the oxygen gas
- As with the gas detection system, an alarm trigger point will be programmed into the automated electrolyser process control system to take appropriate action if a high level of gas is analysed, for example an automated controlled shut down the electrolyser may be invoked

Image credit RAG Underground Sun Storage, Karin Lohberger Photography

## Pressurised alkaline electrolysis process

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During an emergency shutdown of the electrolyser, the gases in the system would be vented to a safe location and a nitrogen gas purge would be initiated

# The ISO 22734 refers to purging with a non-flammable diluent purge gas. Nitrogen is the default choice as an electrolyser purge gas. It is required to ensure safe operation, notably during shut down of the electrolyser.

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**3.27**
**purge gas**
gas used to maintain protective pressurization or to dilute flammable gas or vapour to a concentration well below the lower flammability limit

**3.28**
**purging**
passage of sufficient volume of a *purge gas* (3.27) through a pressurized *enclosure* (3.9) and its ducts, before the application of voltage to the apparatus, to reduce any ignitable (flammable) gas atmosphere to a concentration well below the lower flammability limit

**4.1.4 Purge gas**

Where the use of purge gas is required, the manufacturer shall specify the type of purge gas and its specifications.

**4.5.13 Purge gas quantity**

When the purge gas is supplied in compressed gas containers, there shall be a readily apparent indication of the remaining gas supply. If the quantity of purge gas is insufficient for a proper purge, the hydrogen generator shall not be allowed to start or shall shut down.

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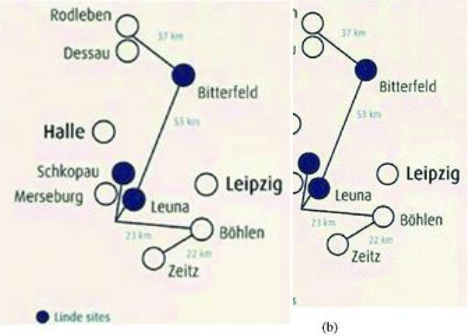
# The safety of hydrogen pipeline transmission and shipping for international trade

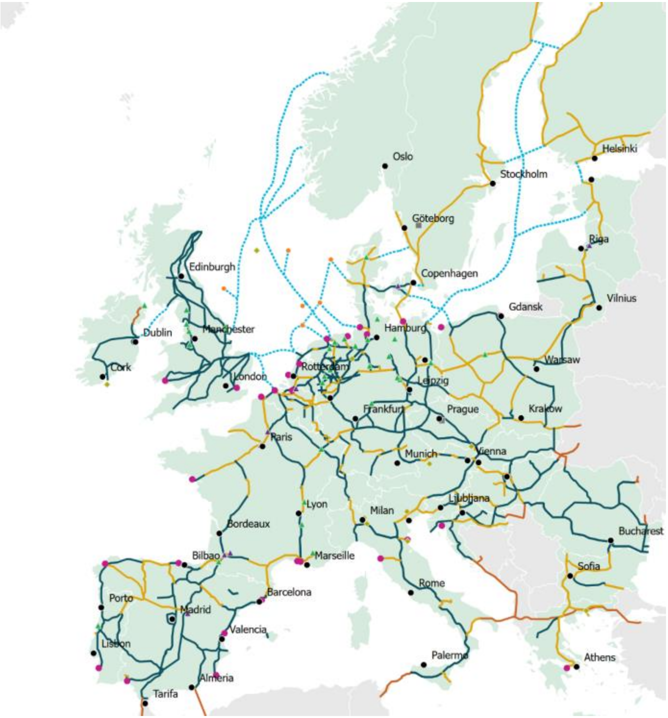
# Industrial gases companies have operated hydrogen transmission pipeline networks in industrial zones for decades. More than 4,000 km of hydrogen pipelines exist worldwide. The expertise exists to build a safe Hydrogen backbone pipeline system.


(a)




(b)


The new, 180-mile pipeline expands our Gulf Coast hydrogen supply network to more than 600 miles, stretching from the Houston Ship Channel in Texas to New Orleans, Louisiana.


https://www.ehb.eu/maps/202204/index.html#5/52.590/32.915
https://www.researchgate.net/figure/e-Hydrogen-pipeline-networks-in-the-North-Europe-and-the-Gulf-Coast-of-Mexico-USA-a_fig3_275462874/download

# Global Energy Ventures (now Provaris), Australia – high pressure compressed hydrogen ship designs.

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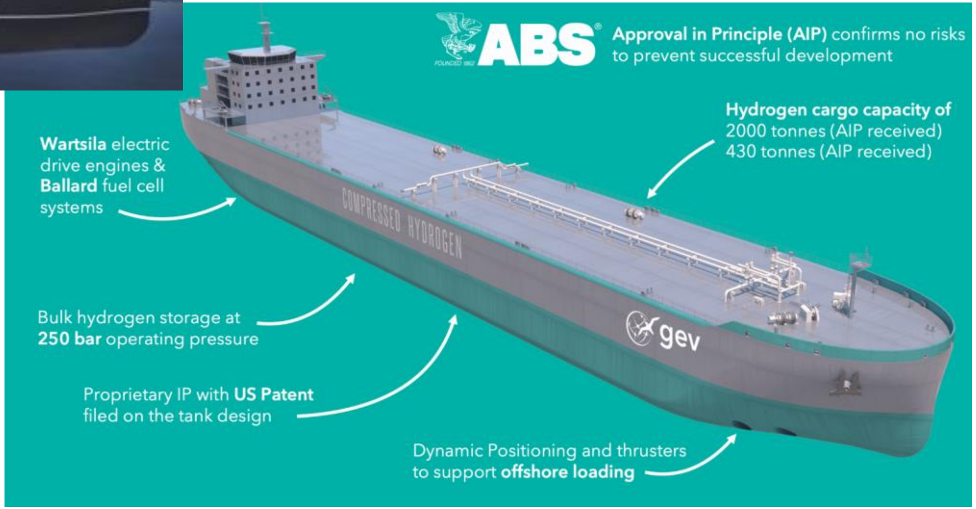




https://www.vesselfinder.com/news/21911-Global-Energy-Ventures-secures-ABS-AiP-for-its-compressed-hydrogen-ship

# Gen2 Energy and Sirius Design & Integration: high-pressure hydrogen compressed gas transportation ships using standard containerised hydrogen storage modules.

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- 190m long ship
- 500x 40-foot standard containers
- Hydrogen propulsion


https://gen2energy.com/gen2-energy-partner-with-sirius-design-integration-to-develop-worlds-first-carrier-for-hydrogen/

# Hydrogen liquefaction can reduce the volume to enable more cost-effective long distance shipping and trade. Hydrogen liquefiers and liquid hydrogen tanker fleets have operated for decades.

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World scale hydrogen liquefaction in USA, 30 tonnes per day, Image: Chart Industries

- Hydrogen is produced as a gas
- To reduce its volume for storage and distribution, hydrogen can be liquefied
- Liquid hydrogen can be transported by road, rail or ship
- The end user will revaporise the liquid hydrogen to gaseous hydrogen prior to use
- It is possible that LH2 will become a traded energy commodity

Sarnia, Canada 30 tonnes per day H2 liquefier
Image courtesy of Air Products and Chemicals, Inc

# Plug Power liquid hydrogen tanker pressure relief valve venting. The flame is directed away from the vehicle and people. Yes, there can be issues, just like there can be with gasoline and diesel tankers.


https://www.linkedin.com/posts/chemsafe_hydrogen-processsafety-chemicalsafety-ugcPost-7059678942114320384-ElsM/?utm_source=share&utm_medium=member_ios
https://233livenews.wordpress.com/2013/04/23/nigeria-fuel-tanker-explosion-razes-down-buildings/

# LH2 shipping on Suiso Frontier - 1,250 m$^3$ (90 tonnes) LH2 capacity on a modified LPG tanker. First demonstration of LH2 shipping in 2022 to better understand the viability and safety. Yes, there was a fire on board due to the use of an inappropriate type of solenoid valve - lessons can be learned.

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### What happened

On the evening of 25 January 2022, a gas control equipment malfunction occurred on the liquified hydrogen tanker, *Suiso Frontier*, while the ship was berthed in the Port of Hastings, Victoria. The fault resulted in a gas flame briefly propagating onto its deck, however, it did not result in a fire or explosion.

**Download**

Download PDF

→

### What the ATSB found

It was found that the ship's gas combustion unit's (GCU) air fan discharge damper actuators were fitted with the incorrect type of electrical solenoid valves, which subjected the valves to damage during service. During operation on 25 January, one of the solenoid valves failed, resulting in the fan damper closing. With no air, the GCU overheated and the hydrogen flame inside it became unstable and propagated outside the unit's vent on the ship's deck.

The ATSB also found that the GCU control system was not equipped to detect a damper closing during operation, and that automated safety controls intended to detect a malfunction to prevent such an incident were not effective.



The ABTS' investigation has found that the failure of an incorrectly-fitted electrical solenoid valve led to the brief propagation of flame from a liquified hydrogen carrier gas combustion unit's vent stack

https://www.reuters.com/business/environment/worlds-first-hydrogen-tanker-ship-test-cargo-australia-japan-2022-01-20/
https://www.abc.net.au/news/2022-01-21/world-first-hydrogen-tanker-docks-at-port-of-hastings/100769138
https://sustainabilityscott.com/blog/
https://www.atsb.gov.au/publications/investigation_reports/2022/mair/mo-2022-001

# Kawasaki Heavy Industries – 160,000 $m^3$ in 4x 43m diameter spherical tanks for mid-distance LH2 shipping. Builds on the Suiso Frontier demonstration experience.

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NIPPON KAIJI KYOKAI

Document No: KF-21HE03998

Date: 28 April 2021

*Approval in Principle*

**KAWASAKI HEAVY INDUSTRIES, LTD.**

*Cargo Containment System for 160,000m3 Liquefied Hydrogen Carrier*

Nippon Kaiji Kyokai (ClassNK) has examined the documents specified in the annex to this letter based on the current Society's Rules and Guidance for the Survey and Construction of Steel Ships *"Part N; Ships Carrying Liquefied Gases in Bulk"* incorporating *"the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code)"*, *"Guidelines for Liquefied Hydrogen Carriers"* incorporating *"INTERNIM RECOMMENDATIONS FOR CARRIAGE OF LIQUEFIED HYDROGEN IN BULK (RESOLUTION MSC.420 (97))"* and other related requirements, and found the design is feasible as basic concept.

Accordingly, Approval in Principle is hereby granted.

Conditions on this approval are set out in the annex to this letter and to be fully taken into account.

( M. Akagi )
General Manager of Hull Department
NIPPON KAIJI KYOKAI

# Hyundai is also considering a liquid hydrogen supply chain to South Korea.

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https://www.maritimeeconomy.com/post-details.php?post_id=bWtsag==&post_name=DNV%20awards%20AiP%20to%20HD%20KSOEs%20hydrogen%20system%20for%20liquefied%20hydrogen%20carrier&segment_name=Ship%20De

# LH2 Europe, mid-sized tanker with 37,500 $m^3$ liquid hydrogen storage capacity, operating from boil-off H2 on fuel cells, proposed by C-Job. Proposed for operations in the North Sea.

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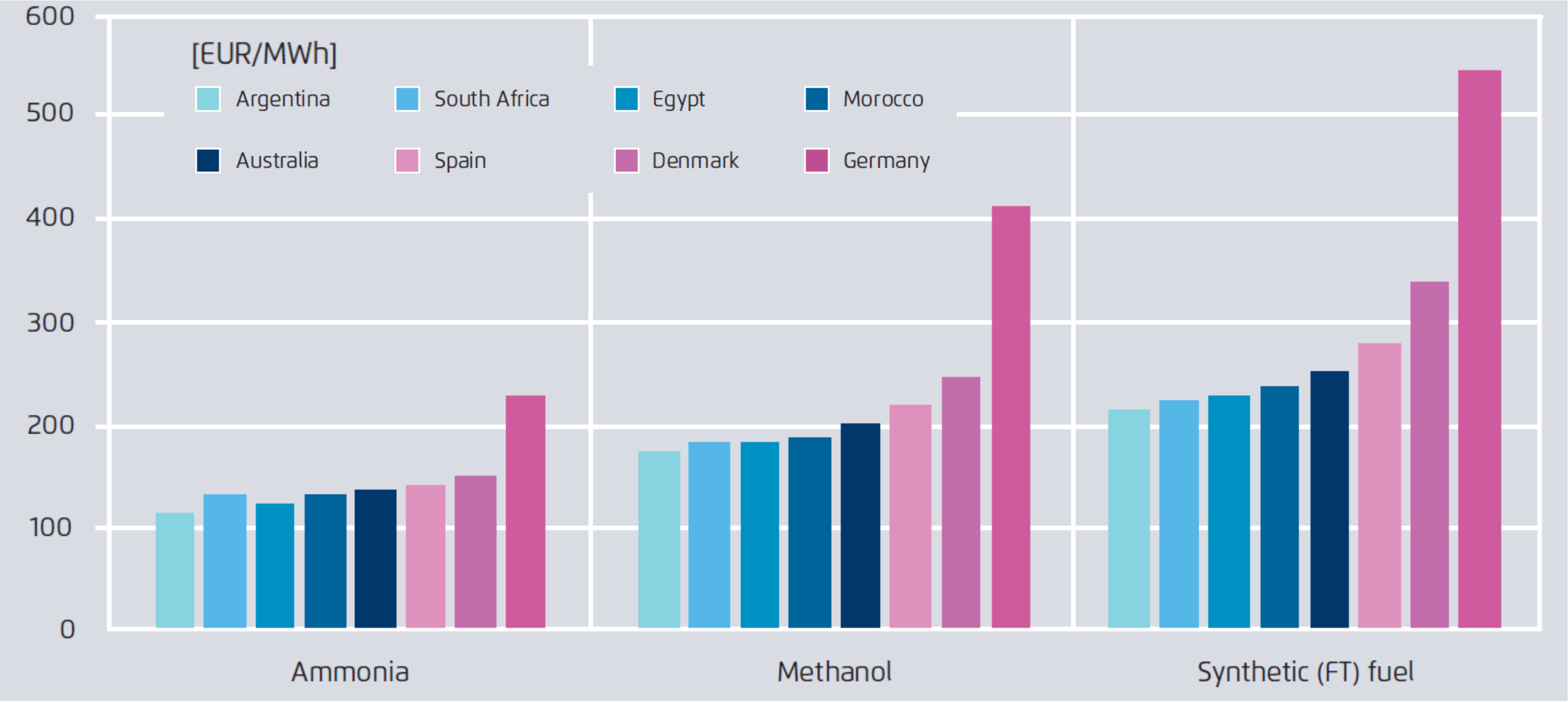
https://c-job.com/press/new-class-of-hydrogen-ship-design-will-revolutionize-renewables-market/

# The need for hydrogen conversion to hydrogen derivatives

Even more losses… why convert hydrogen to hydrogen derivatives?

# Hydrogen derivatives cost more to make than hydrogen, but savings in the supply chain due to easier storage and transportation of liquid energy vectors such as ammonia, methanol and e-fuels can result in a lower total landed cost at the destination.




Agora Energiewende – 12 insights on Hydrogen, Impulse, 245/17-I-2021/EN Nov 2021

# Hydrogen, hydrogen derivatives and e-fuels

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| | Hydrogen Gas | Liquid Hydrogen | Liquid Ammonia | Liquid Methanol | Liquefied Natural Gas (LNG) | Synthetic Aviation Kerosene (SAF) |
|---|---|---|---|---|---|---|
| Ideal universal reaction | Compressed $H_2$ | Liquefied $H_2$ | $3H_2 + N_2 \rightarrow 2NH_3$ | $3H_2 + CO_2 \rightarrow CH_3OH + H_2O$ | $4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$ | $10CO_2 + 31H_2 \rightarrow C_{10}H_{22} + 20H_2O$ |
| Hydrogen yield | 100 % | 100 % | 100 % | 4/6 = 67 % | 4/8 = 50 % | 22/62 = 35.5 % |
| Volumetric energy density, LHV (MJ/L) | 2.43 - 6.8 | 8.52 | 12.7 | 15.7 | 22.2 | 35 |
| Gravimetric energy density, LHV (MJ/kg) | 120 | 120 | 18.6 | 19.9 | 48.6 | 42.2 |
| Infrastructure readiness for large scale deploy-ment in mid-term | Low | Low | High | High | High | High |
| Transportation and storage temperature | Ambient | -253 °C | -33.3 °C | Liquid at ambient temperature | -162 °C | Ambient |
| Transportation and storage phase and pressure | Compressed gas at 250 to 700 bar | Liquid at amos-pheric pressure | Liquid at amospheric pressure | Liquid at amospheric pressure | Liquid at amospheric pressure | Liquid at amospheric pressure |
| Density | 0.017 kg/L | 0.071 kg/L | 0.68 kg/L | 0.79 kg/L | 0.46 kg/L | 0.83 kg/L |
| Toxicity | Non toxic | Non toxic | TWA 25 ppm | TWA 200 ppm | TWA 1,000 ppm | TWA 30 ppm |
| Flammability (% in air) | | 4 - 74 % | 14.8 - 33.5 % | 6.0 - 36.5 % | 4 - 15 % | 0.7 - 4.8 % |

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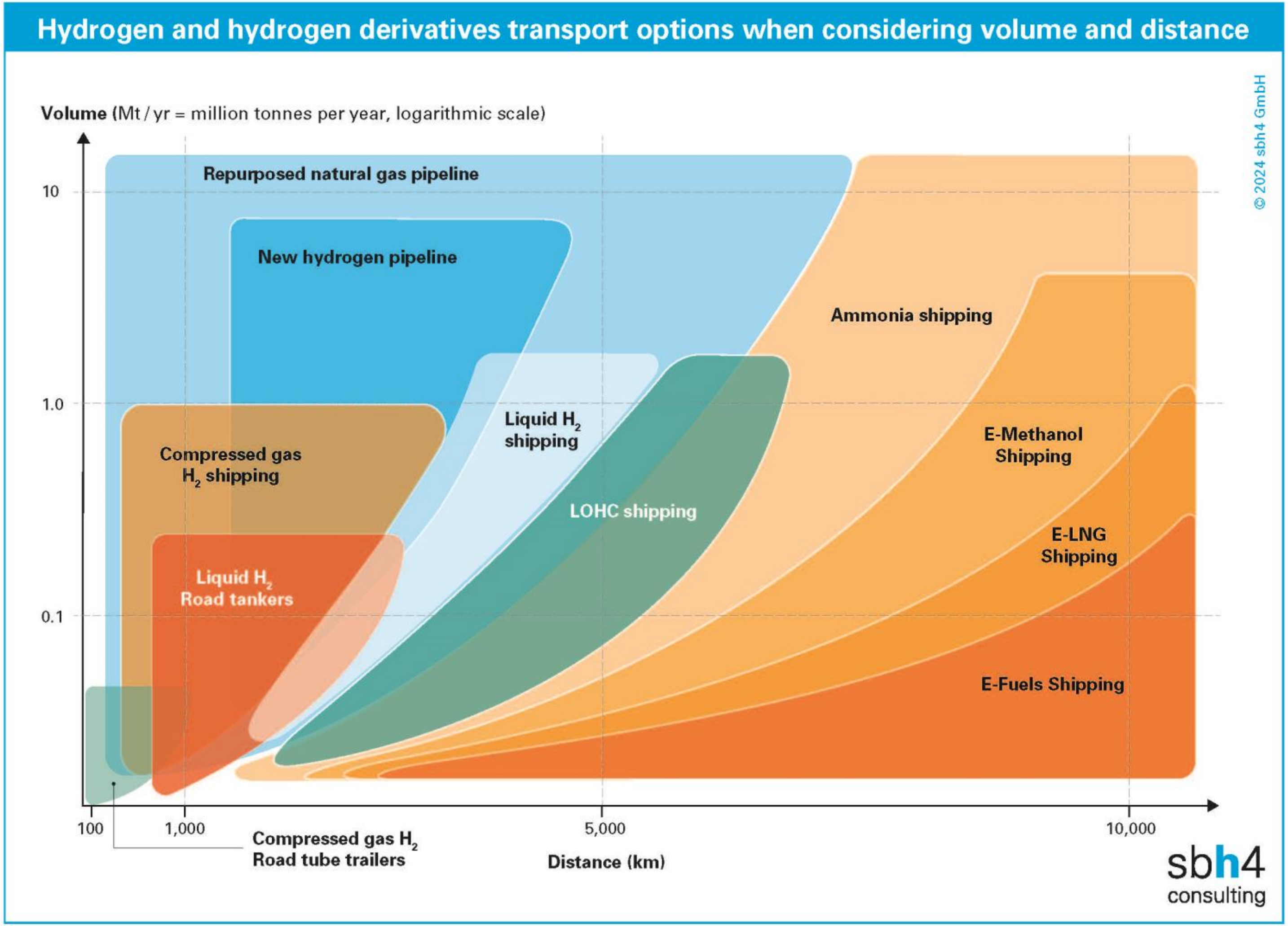
E-Fuels are derived from green hydrogen

- Increasing energy density in e-fuels such as e-methanol, e-LNG and e-SAF comes at the cost of a lower hydrogen yield (higher hydrogen losses) and a higher cost of production

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Hydrogen derivatives such as ammonia can be favourable for long distance shipping of energy vectors as cargoes

- Over long distances and at large scale, the costs of hydrogen conversion to ammonia, methanol or e-fuels can be recovered with shipping cost savings

Some ammonia synthesis processes need nitrogen from a cryogenic nitrogen generator, or ASU. Liquid nitrogen storage is required for backup supply and to offer a variable flowrate to align with variable renewable power. These are very mature technologies. Nitrogen asphyxiation is a potential hazard of ASU operation and nitrogen storage, but it can be mitigated with gas detection.



Images courtesy of APCI

# E-methane, e-methanol and e-SAF projects will need rail, road and river transportation of $CO_2$ to combine with green hydrogen and build hydrocarbons. $CO_2$ has been transported by ship, road and rail for decades.

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# The safety of ammonia as a fuel for mobility on land, water or in the air

# Aviation H2, Australia – plans to use a mixture of cracked ammonia and ammonia as a fuel for modified aviation jet engines. Liquid ammonia is stored on the aircraft.

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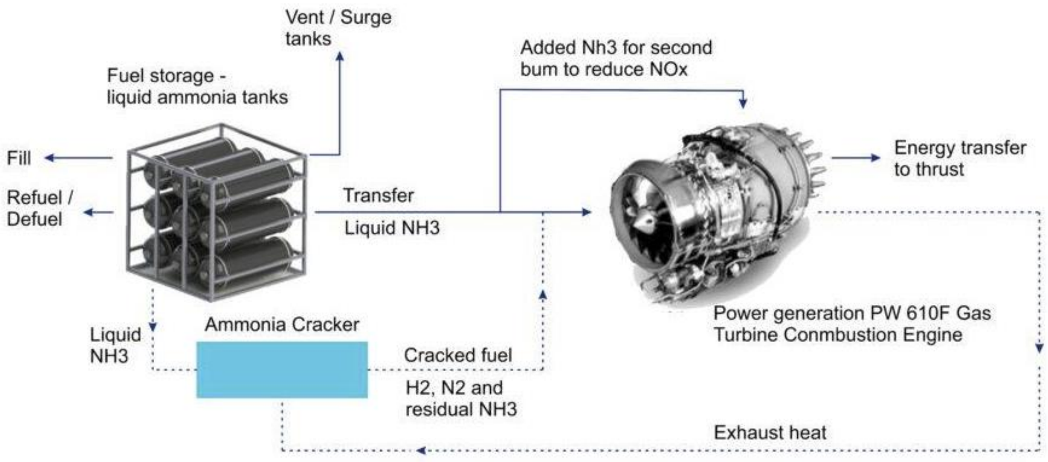


# Ammonigy, Fortesque and Deutsche Bahn have partnered to demonstrate ammonia partial cracking to generate a fuel that can be used on diesel locomotives. Liquid ammonia is stored on the locomotive. These are goods trains, not mass-transit passenger trains.



Image courtesy of Ammonigy

https://www.ammoniaenergy.org/articles/fortescue-deutsche-bahn-to-develop-ammonia-powered-trains-in-germany/

# Amogy proposes to use hydrogen from cracked ammmonia on low temperautre PEM fuel cells (LT PEMFC). Liquid ammonia is stored on the vehicle or vessel. These are heavy duty trucks and tugs, not mass-transit passenger vehicles and ferries.

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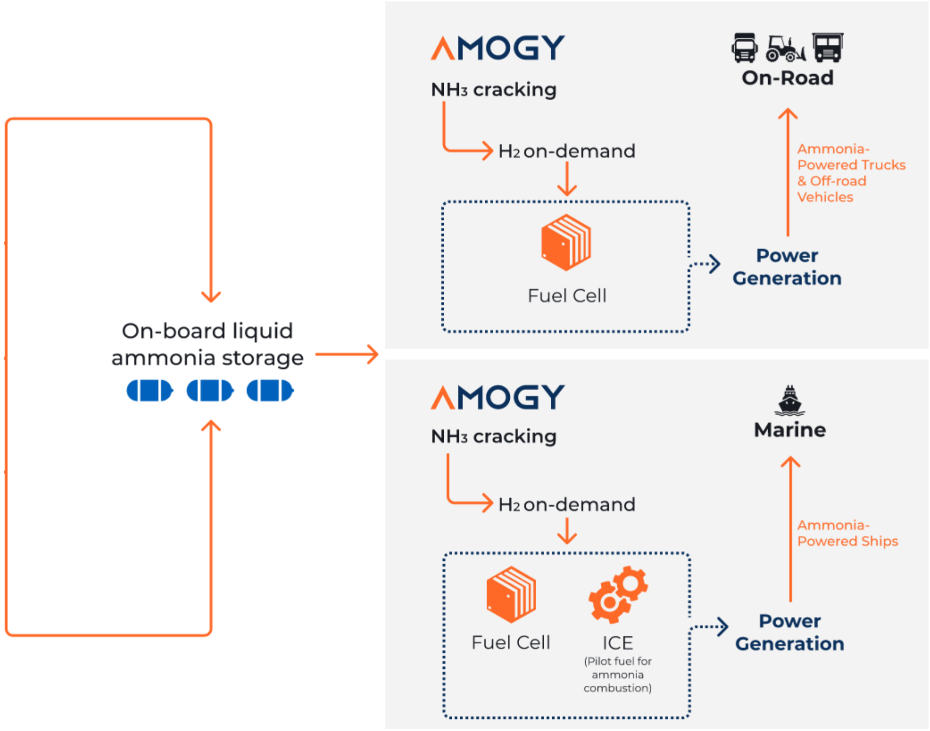



https://www.ammoniaenergy.org/wp-content/uploads/2020/12/Camel-Makhloufi.pdf
https://amogy.co/technology/

## Ammonia offers the promise of being a hydrogen carrier for maritime fuel cells. Bertha B, Viking Energy and Ocean Infinity (fleet of 8 vessels). These are energy sector services vessels, not passenger ferries.

https://www.wartsila.com/encyclopedia/term/platform-supply-vessel-viking-energy

https://www.offshore-energy.biz/ocean-infinitys-first-two-high-tech-ammonia-ready-armada-ships-head-for-norway

# Ammonia is on the way in as a maritime fuel in combustion engines. Liquid ammonia is stored on the ship as fuel. These are bulk cargo vessels and tankers, not cruise liners or ferries.

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- Kriti Future, delivered 10 Jan 2022
- Built for Avin International, Greece
- Jiangsu New Times Shipbuilding, China
- 156,700 tonnes deadweight, 274m long, Suezmax
- ABS LNG level 1 ready and ABS ammonia level 1 ready


- Bocimar has ordered ammonia powered 10 Capesize bulk carriers
- China State Shipbuilding Corp, Beihai, China
- 210,000 tonnes deadweight
- WinGD, two stroke, dual fuel X72DF engines
- Delivery 2025 / 2026

https://www.offshore-energy.biz/worlds-first-ammonia-ready-vessel-delivered/
https://www.offshore-energy.biz/mol-itochu-get-abs-aip-for-ammonia-bunkering-vessel/
https://ww2.eagle.org/content/dam/eagle/rules-and-guides/current/other/325_guide_ammonia_fueled_vessels/ammonia-fueled-vessels-sept21.pdf

# Ammonia storage and product transfer will mean storing and handling large quantities of toxic liquid / gas. Ammonia bunkering infrastructure and maritime standards will develop.

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Yara has odered 15x bunkering terminals from Azane Fuel Solutions


Mistui OSK Lines (MOL) plans ammonia bunkering


https://www.yara.com/news-and-media/news/archive/news-2022/yara-international-and-azane-fuel-solutions-to-launch-worlds-first-carbon-free-bunkering-network-delivering-green-ammonia-fuel-to-the-shipping-industry/
https://www.offshore-energy.biz/mol-itochu-get-abs-aip-for-ammonia-bunkering-vessel/
https://ww2.eagle.org/content/dam/eagle/rules-and-guides/current/other/325_guide_ammonia_fueled_vessels/ammonia-fueled-vessels-sept21.pdf

# Iverson eFuels AS, Norway, start-up in 2027. Renewable power and 240 MW of electrolysis for green hydrogen to produce 200,000 tonnes per year of green ammonia as a maritime fuel. Electrolysis to generate hydrogen and ammonia synthesis / storage are process hazards to be mitigated.

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https://hy2gen.com/feed-study-underway/

# Potential hydrogen, LOHC and ammonia trade in 2050.

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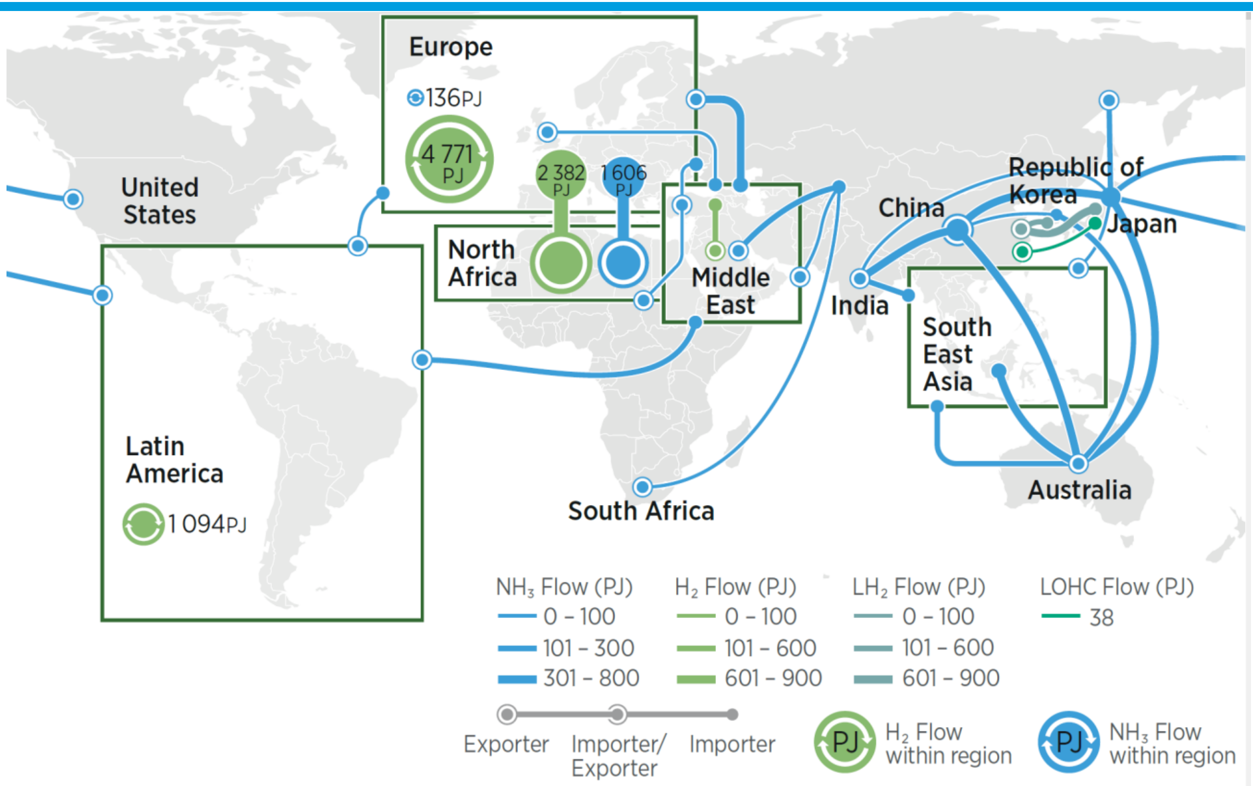


https://www.irena.org/publications/2022/Jul/Global-Hydrogen-Trade-Outlook

# Ammonia infrastructure is mature with 170 ships operating between 120 terminals today. New terminals will be required as the ammonia use cases begin to include energy in addition to current applications for fertilizers and chemicals to energy. Experience from the past can be leveraged.

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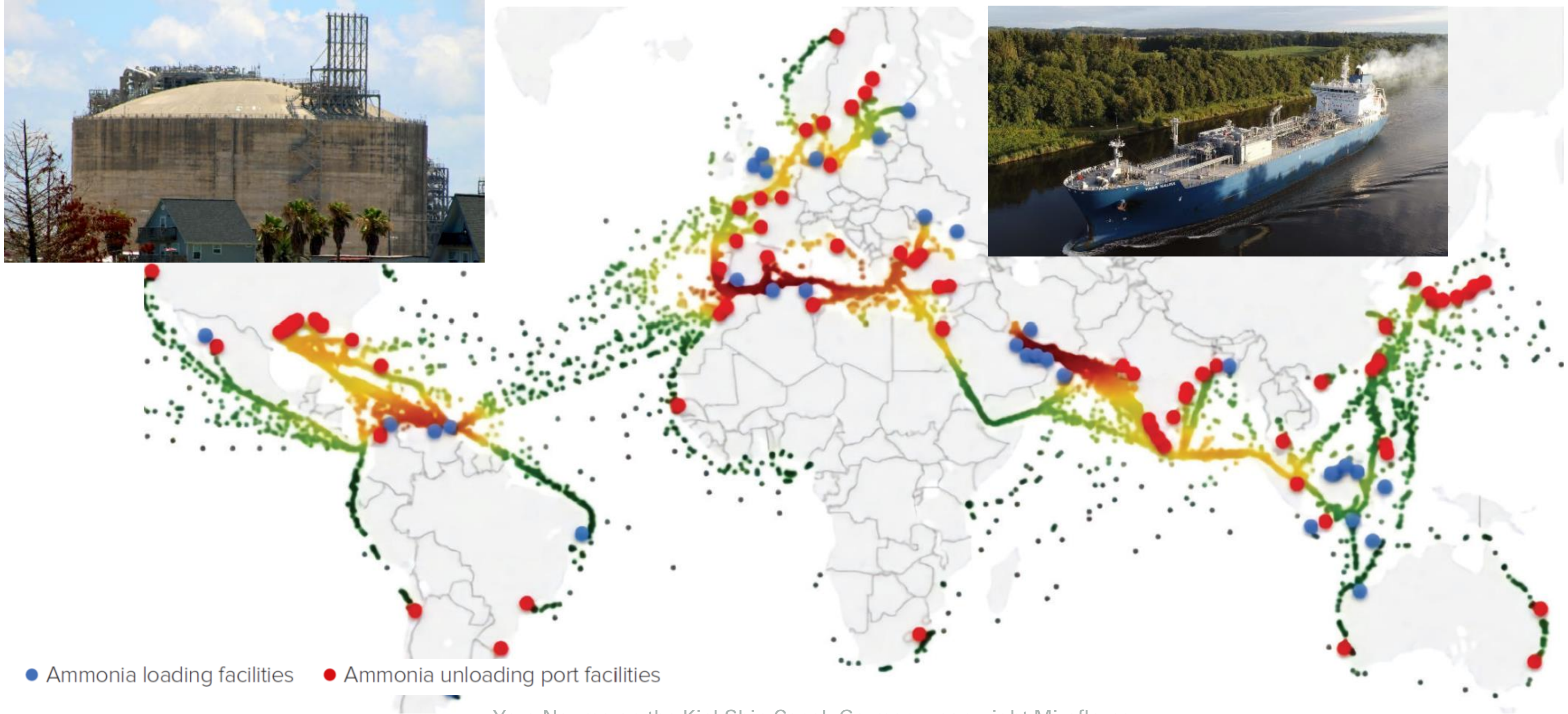


Yara Nauma on the Kiel Ship Canal, Germany, copyright Miraflores

https://royalsociety.org/-/media/policy/projects/green-ammonia/green-ammonia-policy-briefing.pdf

# The Port of Antwerp-Bruges is planning to become a hydrogen and hydrogen derivative transit hub to NW Europe.

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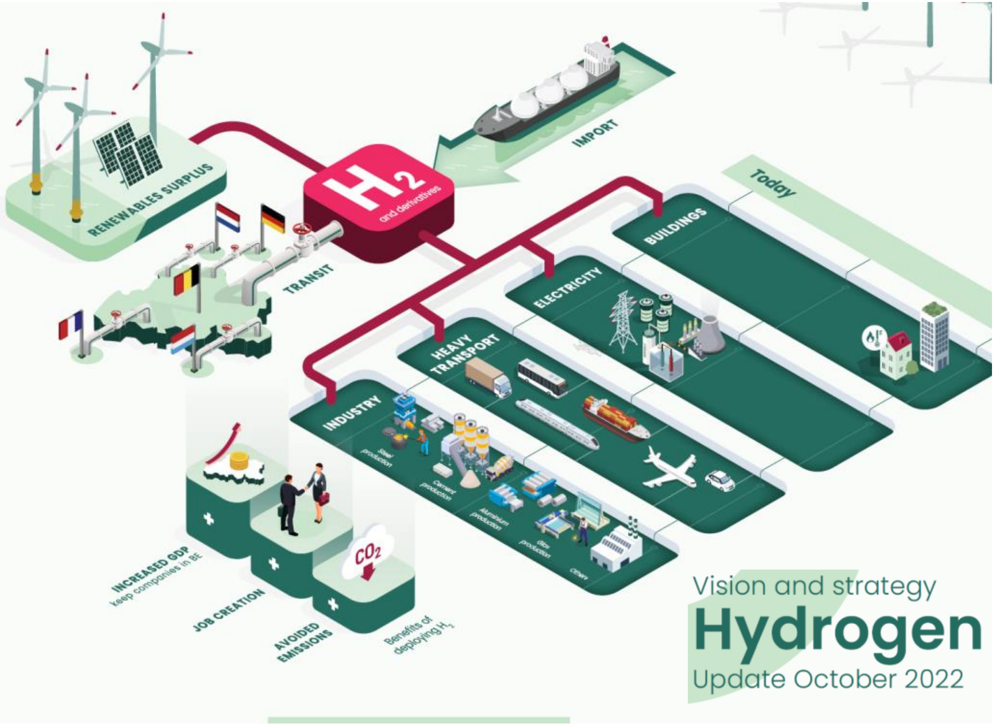


**Pillar 1 – Positioning Belgium as an import and transit hub for renewable molecules in Europe**

| | Measure | First announcement | Status |
|---|---|---|---|
| 1 | Since 2021: Engage with key partners in order to open each one of the 3 main import routes for renewable molecules | ✓ Strategy 2021 | Ongoing (MoUs with Oman and Namibia, identification of partners for the 2 other import routes |
| 2 | In 2022: Support the development of hydrogen import infrastructure to have the first imports of H2-molecules (or of H2-derivatives to be cracked into H2-molecules) by 2026 | ✓ Strategy 2021 | Ongoing (call planned to be launched in early 2023) |
| 3 | In 2023: Organize hydrogen master classes together with the Belgian Hydrogen Council to establish close relationships with key exporting partners | Update 2022 | To be launched in 2023 |
| 4 | In 2023-2024: Investigate how the development of both electricity and hydrogen networks can complement each other in the North Sea | Update 2022 | To be launched once the HNO is designated |

https://economie.fgov.be/sites/default/files/Files/Energy/View-strategy-hydrogen.pdf

# Brunsbüttel is proposed as a new LNG / ammonia import terminal for Germany. Deep sea access, in an industrial chemicals park.

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https://www.cleanenergywire.org/factsheets/liquefied-gas-does-lng-have-place-germanys-energy-future

# The ACE ammonia terminal is proposed for Rotterdam Europort Maasvlakte, with 16.9m draught, used by 400m container ships. Reclaimed land, far from the city: an ideal location for a toxic ammonia storage terminal.

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# Vesta Terminal Flushing, Vlissingen, NL: ammonia import terminal re-vamp using 2x 30,000m$^3$ repurposed tanks and one new tank. Potential for 1,000,000 tonnes per annum ammonia throughput. Ammonia applications for bunkering and cracking to hydrogen for pipeline injection.

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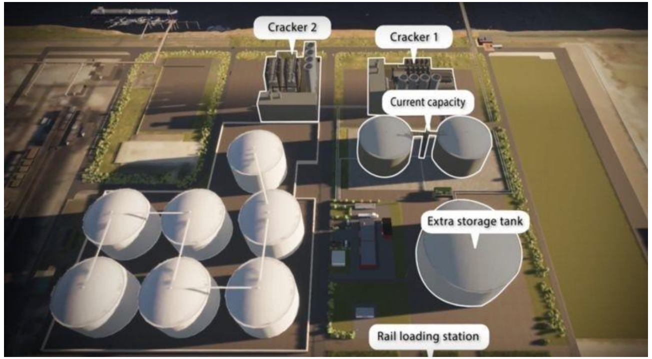


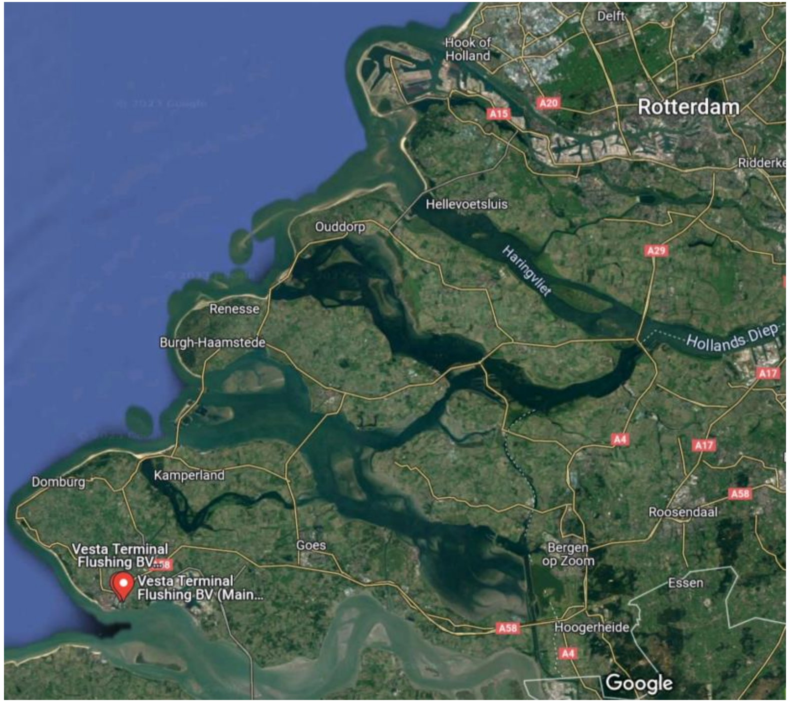


https://protonventures.com/geen-categorie/proton-ventures-awarded-feed-by-vesta-terminals-for-first-independent-ammonia-terminal-of-north-west-europe/

https://issuu.com/marcogeels/docs/portnews_17_2_totaal_lr/s/16252541

# The safety of LOHCs
# Liquid Organic Hydrogen Carriers

# LOHCs are aromatic chemicals with handling and safety properties like diesel. Hydrogenation (exothermic) and dehydrogenation (endothermic) take place over a suitable catalyst.

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https://hydrogen.revolve.media/2022/wp-content/uploads/2022/10/Dehydrogenation-Plant-_Reaction-Area_cropped_min.jpg

# Refined products and crude oil storage terminals exist in relevant locations to import energy. Some can be repurposed for use with LOHCs.

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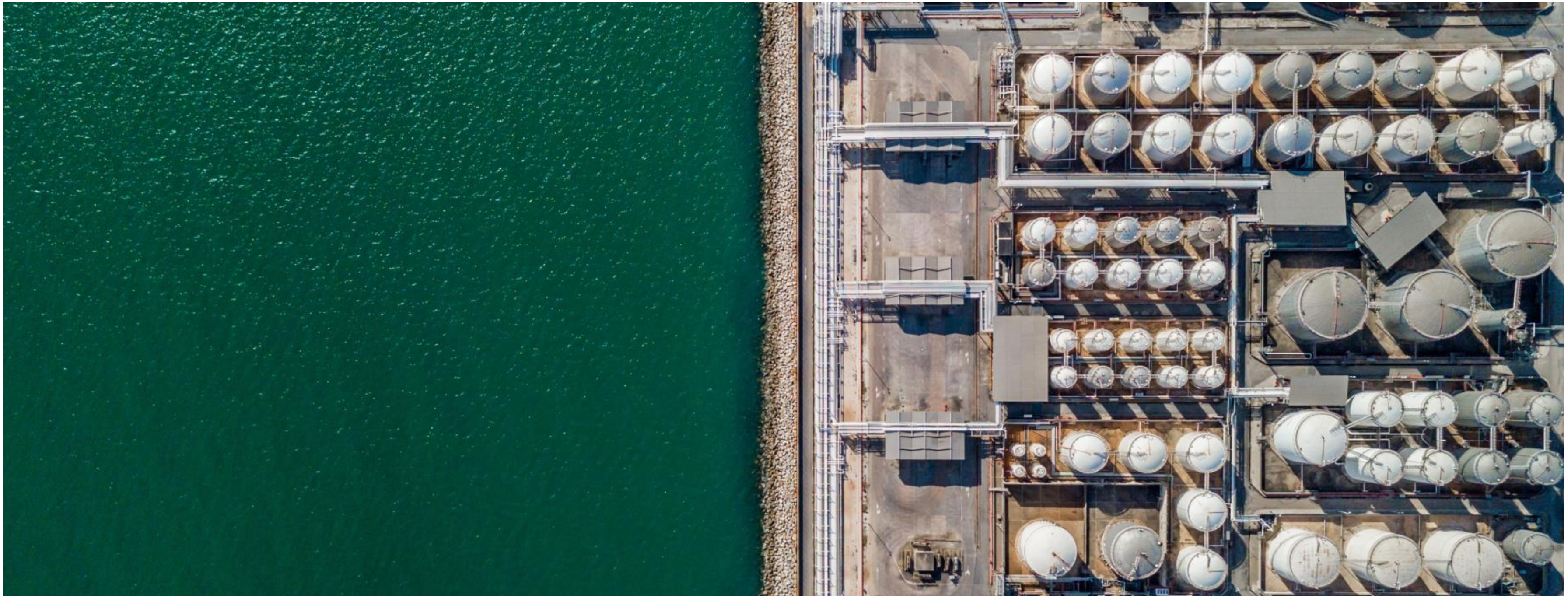

# Hydrogenious LOCH Technologies, benzyltoluene LOHC supply to HRS in Erlangen. LOHC transportation by road tanker, like diesel tanker. Demonstration project to prove the safety and viability.

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https://www.hyplus.de/platz-fuer-wasserstoff-wegbereiter
https://hydrogenious.net/worldwide-novelty-hydrogenious-supplies-hydrogen-filling-station-in-erlangen-germany-via-liquid-organic-hydrogen-carriers/

# Chiyoda hydrogenated toluene (methylcyclohexane, MCH) LOHC shipment on Crane Uranus (a repurposed chemical tanker) from Brunei to Japan in Feb 2022. Demonstration project to prove the safety and viability.

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https://www.chiyodacorp.com/media/20220208_E_R1.pdf

https://www.marinetraffic.com/ja/photos/of/ships/shipid:5744633/ships

# International standards and guidance enotes

# Many ISO/IEC standards and other guidelines exist. And where they do not, demonstrations and pilots will build experience and guide the way.

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**Standards:**
The following standards provide overall guidance across the hydrogen value chain:

**Design:**
- ISO 22734-1 Hydrogen generators using water electrolysis – Industrial, commercial, and residential applications – Part 1: General requirements, test protocols and safety requirements.
- ISO TR 22734-2 Hydrogen generators using water electrolysis – Part 2: Testing guidance for performing electricity grid service.
- ISO 17268 Gaseous hydrogen land vehicle refuelling connection devices ISO 19884 Gaseous hydrogen – Cylinders and tubes for stationary storage.
- ISO 16111 Transportable gas storage devices – Hydrogen absorbed in reversible metal hydride.
- ISO 19880-1 Gaseous hydrogen – Fuelling stations – Part 1: General requirements
- ISO 19880-3 Gaseous hydrogen – Fuelling stations – Part 3: Valves
- ISO 19880-5 Gaseous hydrogen – Fuelling stations – Part 5: Dispenser hoses and hose assemblies ISO 19880-6 Gaseous hydrogen – Fuelling stations – Part 6: Fittings
- ISO 19880-7 Gaseous hydrogen – Fuelling stations – Part 7: O-rings
- ISO 19880-8:2019 Gaseous hydrogen – Fuelling stations – Part 8: Fuel quality control
- ISO/CD 19880-9 Gaseous hydrogen – Fuelling stations – Part 9: Sampling for fuel quality analysis
- IEC 60079-10 series on Area Classification
- IEC 60079-14 Installation
- IEC 60079-17 Inspection
- IEC 60079-19 Repair and Overhaul of Equipment
- ISO/TR 15916, Basic Safety considerations for safety of hydrogen systems.
- ISO 16110 series Hydrogen generators
- ISO 17268 - Gaseous hydrogen land vehicle refuelling connection devices.
- ISO 19880 series- Gaseous hydrogen – Fuelling stations
- ISO 19882 Gaseous hydrogen – Thermally activated pressure relief devices for compressed hydrogen vehicle fuel containers
- ISO 26142 Hydrogen detection apparatus – Stationary applications
- IECEx Certification System via IECEx OD 290 Standardised approach to Testing and Certification of Hydrogen dispensing Equipment and Systems

**Installation and infrastructure:**
- ISO 19880-x series – Gaseous hydrogen – Fuelling stations
- IEC 60079-x series – General requirements for construction, testing and marking of Ex Equipment and Ex Components intended for use in explosive atmospheres.
- ISO 22734-1 Hydrogen generators using water electrolysis – Industrial, commercial, and residential applications – Part 1: General requirements, test protocols and safety requirements.
- ISO TR 22734-2 Hydrogen generators using water electrolysis – Part 2: Testing guidance for performing electricity grid service.
- ISO 19884 Gaseous hydrogen – Cylinders and tubes for stationary storage
- ISO 16111 Transportable gas storage devices – Hydrogen absorbed in reversible metal hydride ISO.
- CEN Standard EN16325
- ISO/TR 15916, Basic Safety considerations for safety of hydrogen systems.
- ISO 16110 series Hydrogen generators
- ISO 17268 - Gaseous hydrogen land vehicle refuelling connection devices.
- ISO 26142 Hydrogen detection apparatus – Stationary applications
- IEC 80069

**Operation and maintenance:**
- ISO 19881 Gaseous hydrogen – Land vehicle fuel containers
- ISO 19882 Gaseous hydrogen – Thermally activated pressure relief devices for compressed hydrogen vehicle fuel containers
- ISO 19885-1 Gaseous hydrogen – Fuelling protocols for hydrogen-fuelled vehicles – Part 1: Design and development process for fuelling protocols
- ISO 19885-2 Gaseous hydrogen – Fuelling protocols for hydrogen-fuelled vehicles – Part 2: Definition of communications between the vehicle and dispenser control systems
- ISO 19885-3 Gaseous hydrogen – Fuelling protocols for hydrogen-fuelled vehicles – Part 3: High flow hydrogen fuelling protocols for heavy duty road vehicles.
- ISO 19887 Gaseous Hydrogen – Fuel system components for hydrogen fuelled vehicles.
- ISO 21087:2019 - Gas analysis – Analytical methods for hydrogen fuel – Proton exchange membrane (PEM) fuel cell applications for road vehicles
- IEC 60079-10 series – Area classification (needs to form part of routine inspection plan)
- IEC 60079-17 – Inspection
- IEC 60079-19 Repair and Overhaul
- IEC 62990 series – Gas detectors
- IEC 60079-29-2 Gas detectors – Selection, installation, use and maintenance of detectors for flammable gases and oxygen.
- IEC 60079-29-3 Gas detectors – Guidance on functional safety of fixed gas detection systems
- IEC/IEEE 60079-30-1 Electrical resistance trace heating – Application guide for design, installation, and maintenance
- IEC 60079-32-1 Electrostatic hazards, guidance
- IEC 60079-43 Equipment in adverse service conditions
- ISO 26142 Hydrogen detection apparatus – Stationary applications
- IEC 62282 series, Fuel cell technologies (currently 29 standards in the series) via IEC TC 105

**Safety:**
- ISO/TR 19516
- ISO 26142
- IEC 60079-29 series
- ISO 16110-1 Hydrogen generators using fuel processing technologies – Part 1: Safety
- ISO/TR 15916 – Basic considerations for the safety of hydrogen systems
- ISO/IEC 80079

**Metrology:**
The following metrological standards provide overall guidance to the green hydrogen sector:
- OIML R137 – Gas Meters
- OIML R139 – Compressed Gaseous Fuel Measuring Systems for Vehicles
- OIML R140 – Measuring Systems for Gaseous Fuels
- Standards issued by ISO/TC193 and ISO/TC193/SC1
- ISO 14687 – Hydrogen fuel quality
- ISO 21087 – Analytical methods for hydrogen fuel

**Certification:**
The International Electrotechnical Commission (IEC) Conformity Assessment Systems allows multiple international conformity assessment bodies to participate in these systems based on a rigorous peer assessment qualification process. Ideally green hydrogen is produced from energy generated by renewable energy sources and verified by harmonized conformity assessment processes. Countries with advanced quality infrastructure systems have internationally recognized conformity assessment bodies, already

# Hydrogen production techniques

| Reformation | |
|---|---|
| **Code/Standard** | **Title** |
| ASME B31.12 | Hydrogen piping and pipelines |
| EIGA Doc 155/09/E | Best available techniques for hydrogen production by steam methane reforming |
| EIGA Doc 183/13/E | Best Available Techniques for the Co-Production of Hydrogen, Carbon Monoxide & their Mixtures by Steam Reforming |
| EIGA Doc 122/18 | Environmental impacts of hydrogen plants |
| EIGA Doc 220/19 | Environmental Guidelines for Permitting Hydrogen Plants Producing Less Than 2 Tonnes Per Day |
| ISO/TR 15916 | Basic considerations for the safety of hydrogen systems |
| ISO 16110 | Hydrogen generators using fuel processing technlolgies |
| NFPA 2 | Hydrogen technologies Code |
| NFPA 497 | Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapors and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas |

| Electrolysis | |
|---|---|
| **Code/Standard** | **Title** |
| ASME B31.12 | Hydrogen piping and pipelines |
| EIGA Doc 122/18 | Environmental impacts of hydrogen plants |
| EIGA Doc 220/19 | Environmental Guidelines for Permitting Hydrogen Plants Producing Less Than 2 Tonnes Per Day |
| ISO/TR 15916 | Basic considerations for the safety of hydrogen systems |
| ISO 22734 | Hydrogen generators using water electrolysis — Industrial, commercial, and residential applications. |
| NFPA 2 | Hydrogen technologies Code |

# Compressed hydrogen gas

| General | |
|---|---|
| **Code/Standard** | **Title** |
| ASME B31.12 | Hydrogen piping and pipelines |
| ISO/TR 15916 | Basic considerations for the safety of hydrogen systems |
| NFPA 55 | Compressed Gases and Cryogenic Fluids Code |
| NFPA 2 | Hydrogen technologies Code |

| Pressurized containers | |
|---|---|
| **Code/Standard** | **Title** |
| ASME B31.12 | Hydrogen piping and pipelines |
| ASME STP/PT-0005 | Design Factor Guidelines for High-Pressure Composite Hydrogen Tanks |
| ASME/STP-PT-014 | Data Supporting Composite Tank Standards Development for Hydrogen Infrastructure Applications |
| CGA H-5 | Standard for Bulk Hydrogen Supply Systems |
| EIGA Doc 100/11 | Hydrogen Cylinders and Transport Vessels |
| EIGA Doc 171/12 | Storage of Hydrogen in Systems Located Underground |
| EN 10229 | Evaluation of resistance of steel products to hydrogen induced cracking (HIC). |
| ISO/TR 15916 | Basic considerations for the safety of hydrogen systems |
| ISO 11114 | Transportable gas cylinders — Compatibility of cylinder and valve materials with gas contents |
| ISO 17081 | Method of measurement of hydrogen permeation and determination of hydrogen uptake and transport in metals by an electrochemical technique |
| ISO 7539-11 | Corrosion of metals and alloys — Stress corrosion testing — Part 11: Guidelines for testing the resistance of metals and alloys to hydrogen embrittlement and hydrogen-assisted cracking |
| NFPA 2 | Hydrogen technologies Code |
| NFPA 55 | Compressed Gases and Cryogenic Fluids Code |

| Compressed hydrogen - Truck, train, ship | |
|---|---|
| **Code/Standard** | **Title** |
| ASME STP/PT-0005 | Design Factor Guidelines for High-Pressure Composite Hydrogen Tanks |
| ASME/STP-PT-014 | Data Supporting Composite Tank Standards Development for Hydrogen Infrastructure Applications |
| CGA H-5 | Standard for Bulk Hydrogen Supply Systems |
| EIGA Doc 100/11 | Hydrogen Cylinders and Transport Vessels |
| EN 10229 | Evaluation of resistance of steel products to hydrogen induced cracking (HIC). |
| ISO/TR 15916 | Basic considerations for the safety of hydrogen systems |
| ISO 17081 | Method of measurement of hydrogen permeation and determination of hydrogen uptake and transport in metals by an electrochemical technique |
| ISO 7539-11 | Corrosion of metals and alloys — Stress corrosion testing — Part 11: Guidelines for testing the resistance of metals and alloys to hydrogen embrittlement and hydrogen-assisted cracking |
| NFPA 2 | Hydrogen technologies Code |
| NFPA 55 | Compressed Gases and Cryogenic Fluids Code |

| Compressed hydrogen - Pipeline | |
|---|---|
| **Code/Standard** | **Title** |
| ASME B31.12 | Hydrogen piping and pipelines |
| EIGA Doc 121/14 (CGA G-5.6) | Hydrogen Pipeline Systems |
| EN 10229 | Evaluation of resistance of steel products to hydrogen induced cracking (HIC). |
| ISO/TR 15916 | Basic considerations for the safety of hydrogen systems |
| ISO 17081 | Method of measurement of hydrogen permeation and determination of hydrogen uptake and transport in metals by an electrochemical technique |
| ISO 7539-11 | Corrosion of metals and alloys — Stress corrosion testing — Part 11: Guidelines for testing the resistance of metals and alloys to hydrogen embrittlement and hydrogen-assisted cracking |
| NFPA 2 | Hydrogen technologies Code |
| NFPA 55 | Compressed Gases and Cryogenic Fluids Code |

# Liquid hydrogen and cryogenics

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| Thermally insulated containers | |
|---|---|
| **Code/Standard** | **Title** |
| ASME B31.12 | Hydrogen piping and pipelines |
| CGA H-3 | Standard for Cryogenic Hydrogen Storage |
| CGA H-5 | Standard for Bulk Hydrogen Supply Systems |
| CGA P-28 | OSHA Process Safety Management and EPA Risk Management Plan Guidance Document for Bulk Liquid Hydrogen Systems |
| EN 1797 | Cryogenic vessels - Gas/material compatibility |
| EN 10229 | Evaluation of resistance of steel products to hydrogen induced cracking (HIC). |
| EIGA Doc 06/19 | Safety in storage, handling and distribution of liquid hydrogen |
| EIGA Doc 133/14 | Cryogenic vaporisation systems – prevention of brittle fracture of equipment and piping |
| EIGA Doc 24/18 | Vacuum insulated cryogenic storage tank systems pressure protection devices |
| EIGA Doc 151/15 | Prevention of Excessive Pressure during Filling of Cryogenic Vessels |
| EIGA Doc 171/12 | Storage of Hydrogen in Systems Located Underground |
| ISO/TR 15916 | Basic considerations for the safety of hydrogen systems |
| ISO 17081 | Method of measurement of hydrogen permeation and determination of hydrogen uptake and transport in metals by an electrochemical technique |
| ISO 7539-11 | Corrosion of metals and alloys — Stress corrosion testing — Part 11: Guidelines for testing the resistance of metals and alloys to hydrogen embrittlement and hydrogen-assisted cracking |
| NFPA 2 | Hydrogen technologies Code |
| NFPA 55 | Compressed Gases and Cryogenic Fluids Code |

| Liquid hydrogen - Tank truck, tanker, tanker train, tanker ship | |
|---|---|
| **Code/Standard** | **Title** |
| ASME B31.12 | Hydrogen piping and pipelines |
| CGA P-28 | OSHA Process Safety Management and EPA Risk Management Plan Guidance Document for Bulk Liquid Hydrogen Systems |
| EN 10229 | Evaluation of resistance of steel products to hydrogen induced cracking (HIC). |
| EIGA Doc 06/19 | Safety in storage, handling and distribution of liquid hydrogen |
| EIGA Doc 133/14 | Cryogenic vaporisation systems – prevention of brittle fracture of equipment and piping |
| ISO/TR 15916 | Basic considerations for the safety of hydrogen systems |
| ISO 17081 | Method of measurement of hydrogen permeation and determination of hydrogen uptake and transport in metals by an electrochemical technique |
| ISO 7539-11 | Corrosion of metals and alloys — Stress corrosion testing — Part 11: Guidelines for testing the resistance of metals and alloys to hydrogen embrittlement and hydrogen-assisted cracking |
| NFPA 2 | Hydrogen technologies Code |
| NFPA 55 | Compressed Gases and Cryogenic Fluids Code |

| Liquid hydrogen – Ducts | |
|---|---|
| **Code/Standard** | **Title** |
| ASME B31.12 | Hydrogen piping and pipelines |
| EN 10229 | Evaluation of resistance of steel products to hydrogen induced cracking (HIC). |
| EIGA Doc 121/14 (CGA G-5.6) | Hydrogen Pipeline Systems |
| EIGA Doc 133/14 | Cryogenic vaporisation systems – prevention of brittle fracture of equipment and piping |
| ISO/TR 15916 | Basic considerations for the safety of hydrogen systems |
| ISO 17081 | Method of measurement of hydrogen permeation and determination of hydrogen uptake and transport in metals by an electrochemical technique |
| ISO 7539-11 | Corrosion of metals and alloys — Stress corrosion testing — Part 11: Guidelines for testing the resistance of metals and alloys to hydrogen embrittlement and hydrogen-assisted cracking |
| NFPA 2 | Hydrogen technologies Code |
| NFPA 55 | Compressed Gases and Cryogenic Fluids Code |

# Fuel cell powered mobility and transportation

| Combustion (On.road, off-road, airplanes, ships) | |
|---|---|
| **Code/Standard** | **Title** |
| ASME B31.12 | Hydrogen piping and pipelines |
| ASTM D7566 | Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons |
| ASTM D4504 | Standard Practice for Evaluation of New Aviation Turbine Fuels and Fuel Additives |
| CGA C-6.4 | Methods for External Visual Inspection of Natural Gas Vehicle (NGV) and Hydrogen Gas Vehicle (HGV) Fuel Containers and Their Installations |
| CGA G-5.4 | Standard for Hydrogen Piping Systems at User Locations |
| CGA H-4 | Terminology Associated with Hydrogen Fuel Technologies |
| EIGA Doc 15/06 | Gaseous Hydrogen Stations |
| EN 17127 | Outdoor hydrogen refuelling points dispensing gaseous hydrogen and incorporating filling protocols |
| EN 16942 | Fuels - Identification of vehicle compatibility - Graphical expression for consumer information |
| ISO 19880-1 | Gaseous hydrogen — Fuelling stations-General Requirements |
| ISO/TR 15916 | Basic considerations for the safety of hydrogen systems |
| ISO 13984 | Liquid hydrogen — Land vehicle fuelling system interface |
| ISO 13985 | Liquid hydrogen — Land vehicle fuel tanks. |
| ISO 17268 | Gaseous hydrogen land vehicle refuelling connection devices. |
| ISO 19881 | Gaseous hydrogen — Land vehicle fuel containers |
| ISO 12619 | Road vehicles — Compressed gaseous hydrogen (CGH2) and hydrogen/natural gas blends fuel system components |
| ISO 21266 | Road vehicles — Compressed gaseous hydrogen (CGH2) and hydrogen/natural gas blends fuel systems |
| SAE J2600 | Compressed Hydrogen Surface Vehicle Fueling Connection Devices |
| SAE J2601 | Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles |
| NFPA 2 | Hydrogen technologies Code |
| NFPA 55 | Compressed Gases and Cryogenic Fluids Code |

| Fuel cells (on-road, off-road, airplanes, ships) | |
|---|---|
| **Code/Standard** | **Title** |
| ASME B31.12 | Hydrogen piping and pipelines |
| CGA C-6.4 | Methods for External Visual Inspection of Natural Gas Vehicle (NGV) and Hydrogen Gas Vehicle (HGV) Fuel Containers and Their Installations |
| CGA G-5.4 | Standard for Hydrogen Piping Systems at User Locations |
| CGA H-4 | Terminology Associated with Hydrogen Fuel Technologies |
| EIGA Doc 15/06 | Gaseous Hydrogen Stations |
| EN 17124 | Hydrogen fuel - Product specification and quality assurance - Proton exchange membrane (PEM) fuel cell applications for road vehicles |
| EN 16942 | Fuels - Identification of vehicle compatibility - Graphical expression for consumer information |
| EN 17127 | Outdoor hydrogen refuelling points dispensing gaseous hydrogen and incorporating filling protocols |
| IEC 62282 | Fuel cell technologies |
| ISO/TR 15916 | Basic considerations for the safety of hydrogen systems |
| ISO 19880-1 | Gaseous hydrogen — Fuelling stations-General Requirements |
| ISO 14687 | Hydrogen fuel quality — Product specification |
| ISO 13984 | Liquid hydrogen — Land vehicle fuelling system interface |
| ISO 13985 | Liquid hydrogen — Land vehicle fuel tanks. |
| ISO 17268 | Gaseous hydrogen land vehicle refuelling connection devices. |
| ISO 19881 | Gaseous hydrogen — Land vehicle fuel containers |
| ISO 12619 | Road vehicles — Compressed gaseous hydrogen (CGH2) and hydrogen/natural gas blends fuel system components |
| ISO 21266 | Road vehicles — Compressed gaseous hydrogen (CGH2) and hydrogen/natural gas blends fuel systems |
| ISO 23273 | Fuel cell road vehicles — Safety specifications — Protection against hydrogen hazards for vehicles fuelled with compressed hydrogen |
| SAE J2719 | Hydrogen Fuel Quality for Fuel Cell Vehicles |
| SAE J2579 | Standard for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles |
| SAE J2600 | Compressed Hydrogen Surface Vehicle Fueling Connection Devices |
| SAE J2601 | Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles |
| SAE AS6858 | Installation of Fuel Cell Systems in Large Civil Aircraft |
| SAE AIR6464 | Hydrogen Fuel Cells Aircraft Fuel Cell Safety Guidelines |
| NFPA 2 | Hydrogen technologies Code |
| NFPA 55 | Compressed Gases and Cryogenic Fluids Code |

# Hydrogen and hydrogen derivatives can safely support decarbonisation and the energy transition

Yes, there are hazards. Yes, the consequences can be severe. Yes, there is risk.

**Risk can be mitigated through appropriate precautions.**
**Yes, we can get this done, safely!**

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consulting

# Introduction to Stephen B. Harrison and sbh4 consulting

sbh4 consulting

**Stephen B. Harrison** is the founder and managing director at sbh4 GmbH in Germany. His work focuses on decarbonisation and greenhouse gas emissions reduction. E-fuels, hydrogen, ammonia and CCTUS are fundamental pillars of his consulting practice.

In support of the European Commission through CINEA in 2023, Stephen evaluated seven CCS, hydrogen and e-fuels submissions to the Third Innovation Fund. The fund allocated €2 billion to large-scale decarbonisation projects in Europe.

Stephen has served as the international expert and team leader for three ADB projects related to CCTUS and renewable hydrogen deployment in Pakistan, Palau and Viet Nam. He has also supported the IFC and work bank on e-fuels and green hydrogen strategy development projects in Namibia and Pakistan. In 2021, he specified more than 2GW of electrolyser capacity for green hydrogen projects. With a background in industrial and specialty gases, including 27 years at BOC Gases, The BOC Group and Linde Gas, Stephen has intimate knowledge of e-fuels, hydrogen, ammonia and carbon dioxide from commercial, technical and operational perspectives. For 14 years, he was a global business leader in these FTSE100 and DAX30 companies.

Stephen has extensive buy-side and sell-side M&A due diligence and investment advisory experience in the energy and clean-tech sectors. Private Equity firms and investment fund managers and green-tech start-ups are regular clients. He also supports operating companies in their mission to decarbonise their scope 1, 2 and 3 GHG emissions.

As a member of the H2 View and **gas**world editorial advisory boards, Stephen advises the direction for the leading hydrogen-focused international publications. Through H2 VIEW, World Hydrogen Leaders and Sustainable Aviation Futures, he has led Masterclasses covering many hydrogen, SAF and hydrogen derivatives themes in virtual and live sessions.

Stephen served on the Scientific Committee for CEM2023 in Barcelona and chaired the session related to CEM from clean energy systems. Stephen was session chair for the e-fuels and hydrogen propulsion track at the Bremen Hydrogen Technology Exhibition in September 2023. He was also conference chair for day-2 of the CO2 utilisation Summit in Hamburg in 2023. Stephen also served on the Technical Committee for the Green Hydrogen Summit in Oman in December 2022 and the Advisory Board of the International Power Summit in Munich in September 2022.