Liquid hydrogen production and shipping

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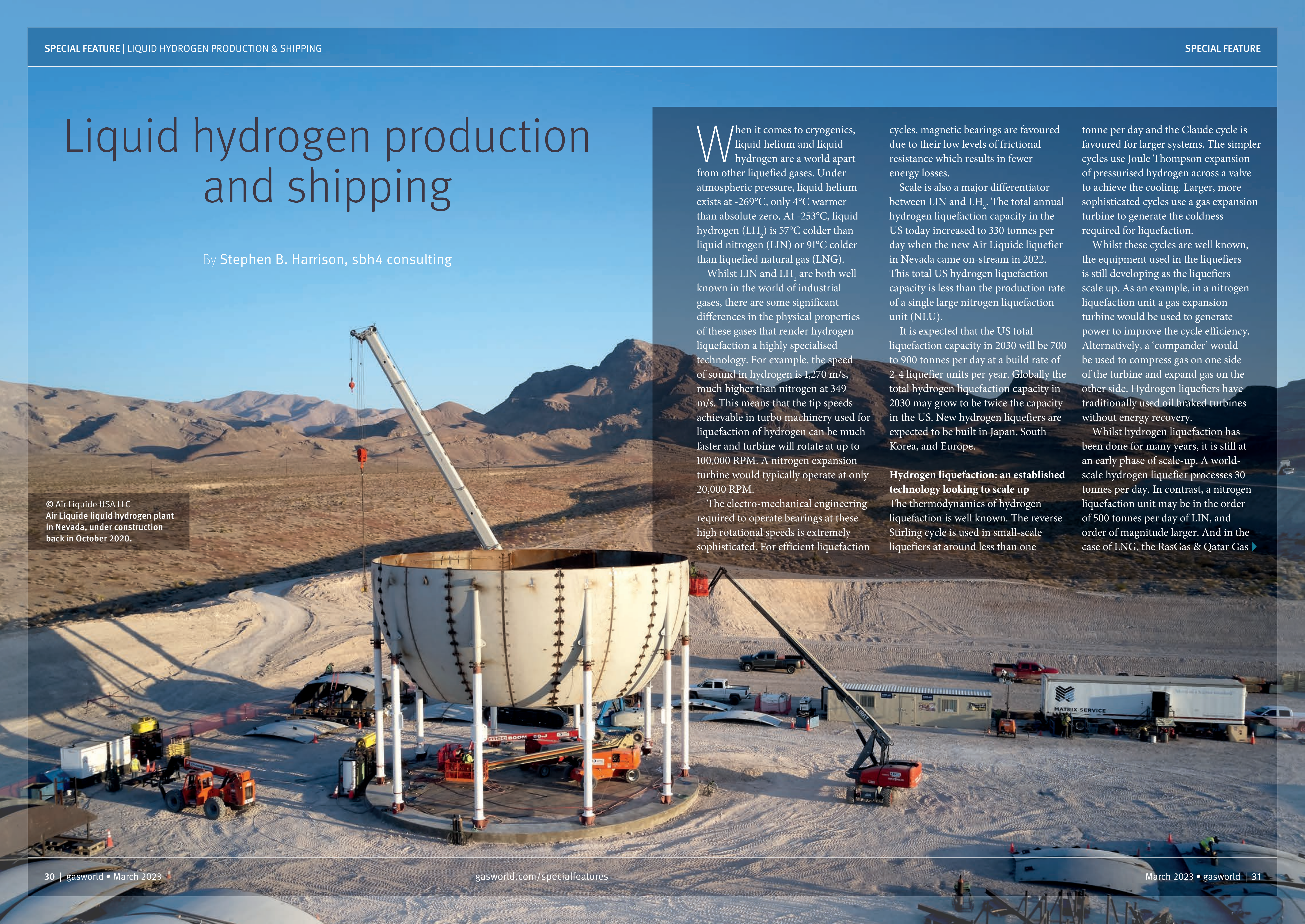


© Air Liquide USA LLC
Air Liquide liquid hydrogen plant in Nevada, under construction back in October 2020.

When it comes to cryogenics, liquid helium and liquid hydrogen are a world apart from other liquefied gases. Under atmospheric pressure, liquid helium exists at -269°C, only 4°C warmer than absolute zero. At -253°C, liquid hydrogen (LH_2) is 57°C colder than liquid nitrogen (LIN) or 91°C colder than liquefied natural gas (LNG).

Whilst LIN and LH_2 are both well known in the world of industrial gases, there are some significant differences in the physical properties of these gases that render hydrogen liquefaction a highly specialised technology. For example, the speed of sound in hydrogen is 1,270 m/s, much higher than nitrogen at 349 m/s. This means that the tip speeds achievable in turbo machinery used for liquefaction of hydrogen can be much faster and turbine will rotate at up to 100,000 RPM. A nitrogen expansion turbine would typically operate at only 20,000 RPM.

The electro-mechanical engineering required to operate bearings at these high rotational speeds is extremely sophisticated. For efficient liquefaction cycles, magnetic bearings are favoured due to their low levels of frictional resistance which results in fewer energy losses.

Scale is also a major differentiator between LIN and LH_2. The total annual hydrogen liquefaction capacity in the US today increased to 330 tonnes per day when the new Air Liquide liquefier in Nevada came on-stream in 2022. This total US hydrogen liquefaction capacity is less than the production rate of a single large nitrogen liquefaction unit (NLU).

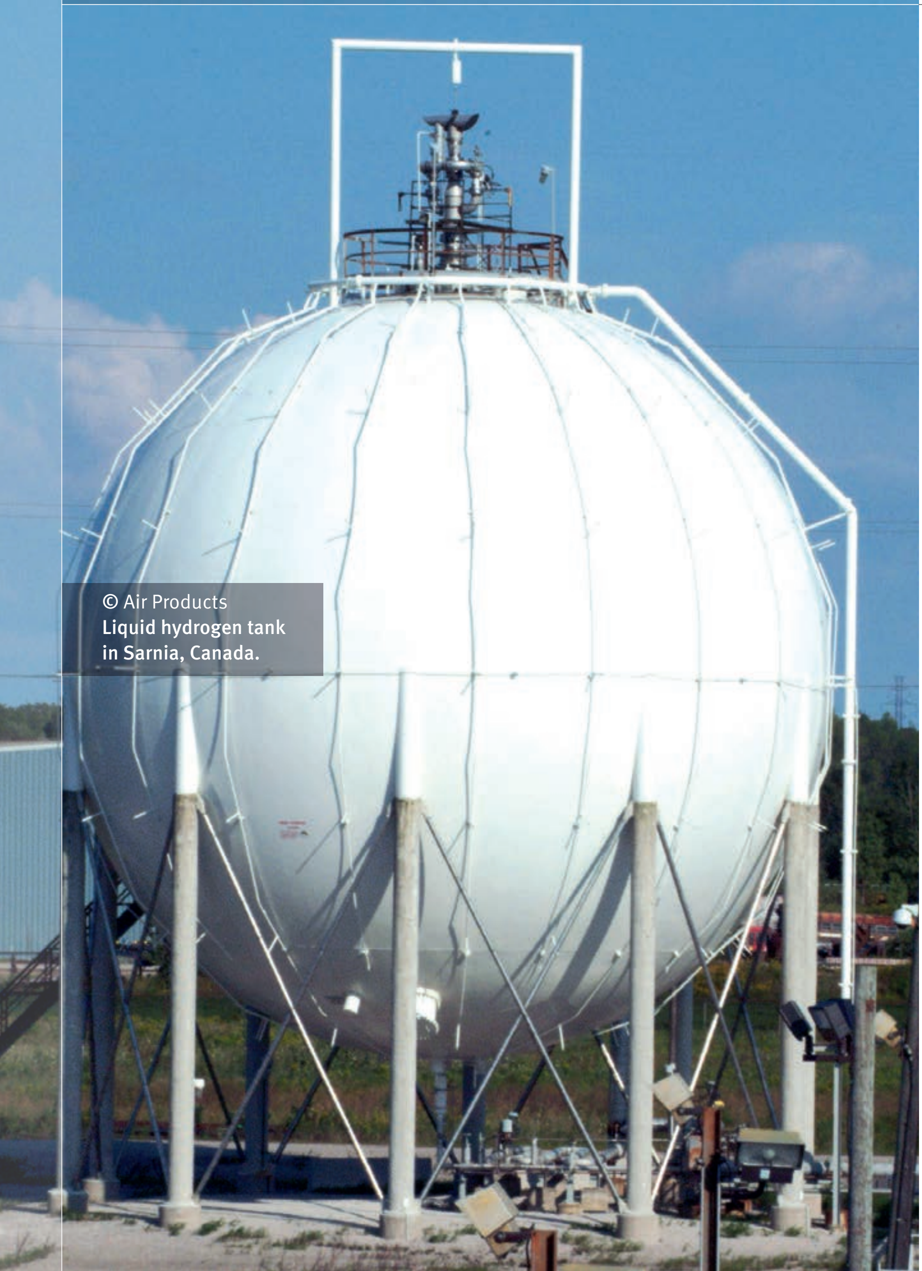
It is expected that the US total liquefaction capacity in 2030 will be 700 to 900 tonnes per day at a build rate of 2-4 liquefier units per year. Globally the total hydrogen liquefaction capacity in 2030 may grow to be twice the capacity in the US. New hydrogen liquefiers are expected to be built in Japan, South Korea, and Europe.

Hydrogen liquefaction: an established technology looking to scale up

The thermodynamics of hydrogen liquefaction is well known. The reverse Stirling cycle is used in small-scale liquefiers at around less than one tonne per day and the Claude cycle is favoured for larger systems. The simpler cycles use Joule Thompson expansion of pressurised hydrogen across a valve to achieve the cooling. Larger, more sophisticated cycles use a gas expansion turbine to generate the coldness required for liquefaction.

Whilst these cycles are well known, the equipment used in the liquefiers is still developing as the liquefiers scale up. As an example, in a nitrogen liquefaction unit a gas expansion turbine would be used to generate power to improve the cycle efficiency. Alternatively, a 'compander' would be used to compress gas on one side of the turbine and expand gas on the other side. Hydrogen liquefiers have traditionally used oil braked turbines without energy recovery.

Whilst hydrogen liquefaction has been done for many years, it is still at an early phase of scale-up. A world-scale hydrogen liquefier processes 30 tonnes per day. In contrast, a nitrogen liquefaction unit may be in the order of 500 tonnes per day of LIN, and order of magnitude larger. And in the case of LNG, the RasGas & Qatar Gas



© Air Products
Liquid hydrogen tank in Sarnia, Canada.

world scale LNG facility processes 100,000 tonnes per day. With the advent of international green hydrogen shipping to transport this clean energy vector, liquefier capacities in the order of hundreds of tonnes per day will be required.

As hydrogen liquefaction scales up, it will be essential to use more efficient thermodynamic cycles to minimise power consumption. The IDEALHY project proposed a cycle with an initial pre-liquefaction cooling phase that used a mixed gas of helium and neon (Nelium) as a refrigerant. Then a sequence of six hydrogen expansion turbines were proposed to optimise the energy efficiency within the latter stages of hydrogen liquefaction. In contrast, a state-of-the-art hydrogen liquefier today might use liquid nitrogen for the initial cooling stages and two stages of expansion in the later stages.

> "A world-scale hydrogen liquefier processes 30 tonnes per day"

An exclusive technology domain

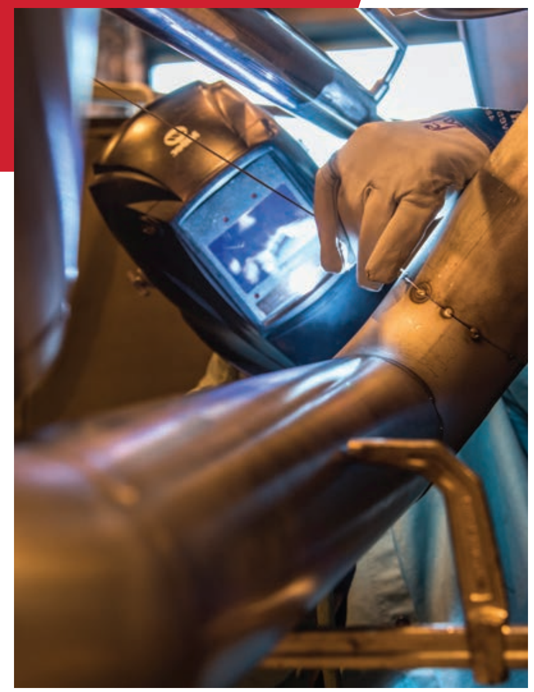
There are only a few companies capable of producing hydrogen liquefiers. Stirling Cryogenics in the Netherlands offers small systems, as does France's Air Liquide through their HYLIAL range. Air Liquide acquired the turboexpander business of Nikkiso Cryogenic Industries in 2021, giving them access to a broader range of equipment that can be used in liquefaction processes.

Linde Kryotechnik in Switzerland and Chart Industries in the US focus on midscale and larger units in the range of 10 to 30 tonnes per day. Air Products has had the capability to produce liquefiers for many years and in 2018 enhanced their capability through their acquisition of Rotoflow™ from Baker Hughes.

Recent entrants to the hydrogen liquefier sector include Plug Power and Kawasaki Heavy Industries (KHI). Plug acquired Joule Processing in 2022 and announced a collaboration with Fives and Atlas Copco Mafi-Trench to develop hydrogen liquefiers to support their emerging liquid hydrogen supply chain. KHI started up their five tonne per day liquefier in Japan in 2020. They plan to offer commercial units up to 25 tonnes per day in size.

Liquid hydrogen shipping: a technology in its infancy

The world's first ocean shipment of liquid hydrogen took place in 2022 when the Suiso Frontier sailed from the Port of Hastings in Australia to Kobe in Japan. The vessel is a converted inshore LPG tanker and has the capacity to carry 1,250m^3 (90 tonnes) of LH_2 in a single cryogenically insulated cylindrical tank. The shipment was part



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HESC Hastings hydrogen liquefier.

of the HYSTRA demonstration project.

KHI, who are a leading player in the HYSTRA project, are planning a larger liquid hydrogen tanker. It would have the capacity of 160,000m³ in four spherical tanks, each with a diameter of 43m. KHI received 'Approval in Principle' for their design in April of 2021. A very large liquid hydrogen storage terminal is in planning at Kobe to receive shipments from this type of tanker.

A mid-sized LH_2 tanker wtih 37,500 m3 of LH_2 storage capacity has been proposed by C-Job Naval Architects. They have developed the concept in partnership with LH_2 Europe who propose to bring liquid hydrogen from North Sea offshore wind-powered green energy islands to onshore markets in norhtern Europe. The vessel would be powered by fuel cells running on hydrogen boil-off from the liquid cargo.

Jamila, a conceptual LH_2 tanker design has been proposed by a study from Cranfield University in the UK. It would have 280,000m³ LH_2 capacity contained in four cylindrical cryogenic tanks. The ship would be 370m long, 75m wide, and draw just over 10m when loaded. It would have a fully loaded displacement of 232,000 tonnes, of which 20,000 tonnes would be the LH_2 cargo. The concept involves using the boil-off gas from the liquid hydrogen storage as propulsion for a 50 MW combined cycle gas turbine engine.

Liquid hydrogen shipping is in ist infancy, as LNG shipping was 50 years ago. Today, a QMax type LNG tanker can carry 266,000m³ (122,360 tonnes) of LNG and is 354m long, 55m wide and with a draft of 12m. Liquid hydrogen shipping still has some way to go.

Liquid hydrogen, compressed hydrogen, or liquid ammonia shipping

Compressed gaseous hydrogen shipping has been proposed by Australia's Global Energy Ventures. It's ship would operate at a pressure of 250 bar and the hydrogen cargo would double up to serve as the fuel for a large Ballard Power Systems fuel cell that would provide propulsion for the ship.

Gen2 Energy and Sirius Design & Integration have proposed a 190m long high-pressure gaseous hydrogen carrier. Hydrogen would be stored in five hundred standard-size 40ʻ container modules. Each module would contain many Type 4 carbon fibre cylinders, similar to those used for hydrogen distribution by road tanker.

The attraction of using liquid hydrogen as an anergy vector is that it has a higher volumetric energy density (8.5 MJ/litre) than compressed hydrogen at 250 bar (2.43 MJ/litre).

"The optimum shipping solution depends largely on the distance involved..."

This means that the size of the LH_2 ship would be about one third the size of a compressed hydrogen ship to carry the same amount of hydrogen. The disadvantage of LH_2 is that the electrical power requirement and capital investment required for liquefaction are both significantly more than for hydrogen compression to 250 bar.

The optimum shipping solution depends largely on the distance involved since the trade-off is between spending money on the ships versus spending money on the shoreside infrastructure and hydrogen preparation. Generally, compressed gaseous hydrogen shipping would be favoured for short distances, such as crossing the Mediterranean from north Africa to Italy.

LH_2 shipping would be optimal for mid-distances, such as the Australia to Japan route. For very long distances, the economics favour investment in conversion of the hydrogen to ammonia to increase the energy density to 12.7 MJ/litre and reduce the shipping operations costs. gw