Interreg North Sea Region
DUAL Ports
European Regional Development Fund
EUROPEAN UNION

POLICY BRIEF
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Offshore Hydrogen Technology

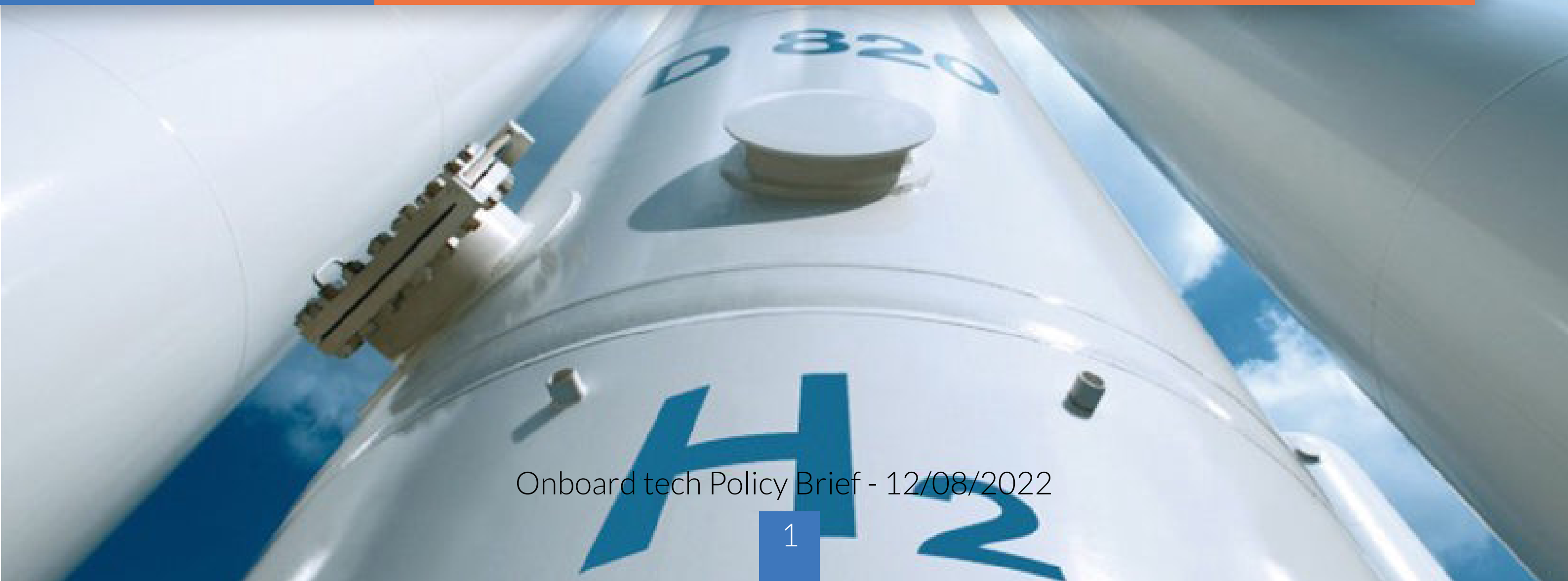
Introduction and Objectives

The up-take of hydrogen fuel in shipping will play a major role in both emissions reductions and the hydrogen economy in the NSR.

The objective of this brief is to provide a high level overview of hydrogen infrastructure technology required for offshore production and bunkering.

THIS BRIEF

1. **Explains available methods of green hydrogen production and their Technology Readiness Levels (TRLs), comparing the advantages and disadvantages of each**
2. **Reviews hydrogen offloading (bunkering) systems in detail for different storage types (gaseous, liquified, containerised) and discusses their application in offshore environments**



Green Hydrogen Production

Alkaline Electrolysers - TRL 9

Commercial Alkaline Electrolysers (AE) have been available for over a century at scales of hundreds of MW, as shown in the image below.

A 135MW alkaline electrolyser facility in Norway, operational from 1953.

Alkaline technology is reliable, well understood and available in multi megawatts. They however, have poor efficiency curves.

Proton Exchange Membrane Electrolysers - TRL 9

Proton Exchange Membrane (PEM) electrolysers were developed in the 1960s and are currently commercially available in systems over 10 MW.

Advantages of PEM over AE:

- Better efficiency curves allowing 10 times the current densities thus significantly reducing footprint;
- Better separation of gases, leading to lower water purity requirements and better efficiency;
- Higher response rates to varying currents, making them more suitable for renewable energy.

Disadvantages of PEM compared to AE:

- PEM requires platinum, iridium and ruthenium catalysis, significantly affecting the cost/kW;
- Constructing large PEM electrolyser stacks is difficult, meaning that the large electrolysers require dozens, or possibly hundreds of stacks, leading to high cost and complexity;
- PEM electrolyser lifetimes are as yet unproven.

Solid Oxide Electrolysers - TRL 6

Solid Oxide Electrolysers (SOE) operate at high temperatures (500 to 1000°C), taking advantage of thermodynamics leading to the splitting of water being more efficient. This step change in efficiency has motivated considerable research in recent years. SOEs are at the large-scale prototype phase, TRL 6.

However, this technology also has the following negative aspects:

- To survive the high temperatures, rare and expensive materials are required;
- The various materials in each cell have slightly different coefficients of thermal expansion, which leads to delamination of layers after repeated heating and cooling cycles. Thus, they operate best with a continuous output.

Offloading Systems

Hydrogen is stored and transported either as either a gas or liquid. It can be transferred through a pipe or hose or delivered in a container. Therefore, the following systems have been considered, which are discussed in detail later:

- Gaseous Hydrogen (GH2) Systems
- Liquid Hydrogen (LH2) Systems
- Containerised Hydrogen Systems (either gaseous or liquid)

Similar to liquified natural gas (LNG), hydrogen can be liquefied before being loaded onto highly-insulated tankers. However, boil-off gas is an issue, even when using active cooling measures. For example, on an eleven-day journey from Australia to Japan, a LH2 carrier vessel could experience losses of up to 2% of cargo. This can be resolved by using the LH2 boil-off as fuel, as on LNG carriers.

At present, there is no standard hydrogen storage pressure for maritime applications. This document makes reference to 350 and 700 bar storage, as this is standard in terrestrial applications.

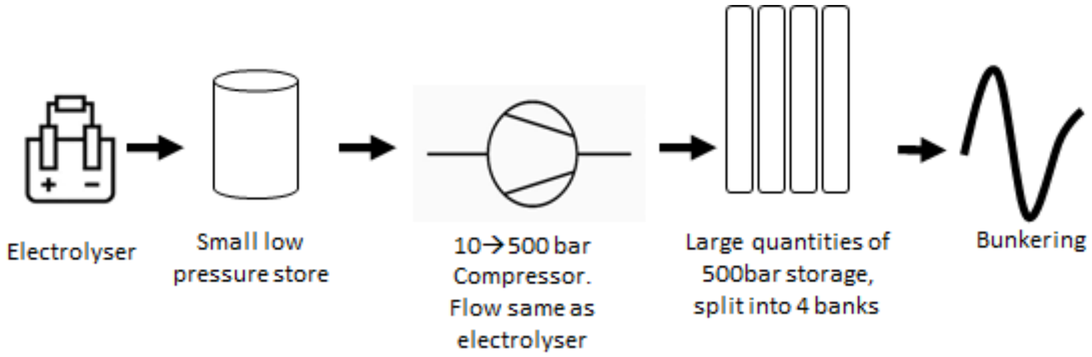
Even if pressurised to 700 bar, the energy density of hydrogen is 1,250 Wh/L (at Lower Heating Value, or LHV), compared to diesel at 10,720 Wh/L and petrol at 9,500 Wh/L. However, as a diatomic gas, hydrogen has a compressibility factor of <1, meaning that the density is lower than expected at high pressure. When liquefied (-252°C at atmospheric pressure), the energy density increases to 2,360 Wh/L (LHV).

Gaseous Hydrogen Bunkering

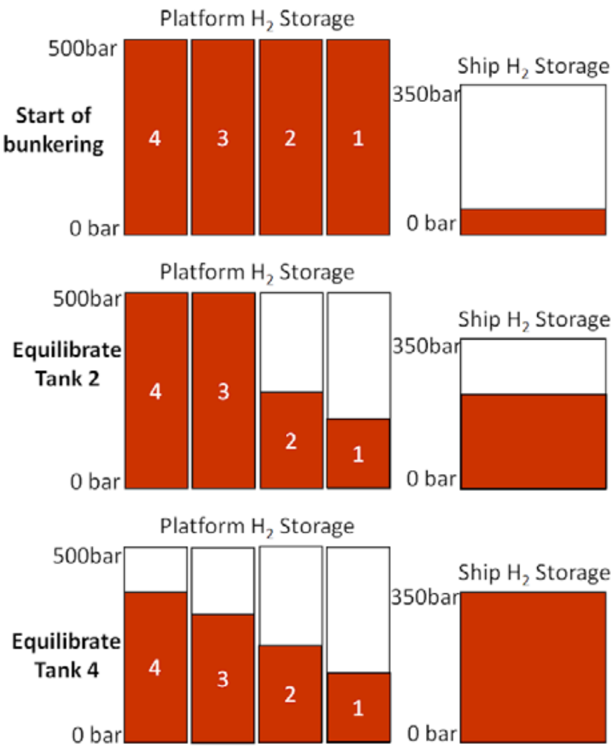
Hydrogen is produced at low pressure, typically 20 to 30 bar and is eventually transferred to the ship via a flexible hose. The two methods for transfer of gaseous hydrogen are cascade and direct pressure filling.

Cascade filling

The hydrogen storage is filled to a higher pressure than the target pressure for the ship's tanks (typical numbers would be 350 bar target pressure in the ship and 500 bar storage on the platform). The storage is divided into multiple banks of pressure vessels. Each bank is then opened in turn to the ship's depleted storage and the gas is transferred as the pressure between the ship and the platform equalises. After the first bank is opened, the pressure in both the ship and the platform storage vessels may be ~250 bar. On opening the second bank, the pressure will level at 300 bar, the third at 325 bar and finally, the fourth bank will level at the desired 350 bar.



A schematic representation of the equipment required for cascade filling

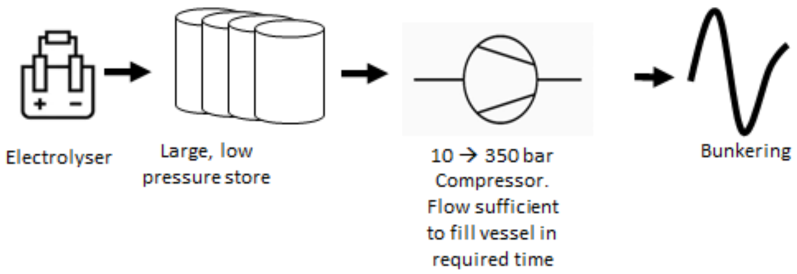


Schematic diagram showing the principle of cascade filling

Direct pressure filling

In this method hydrogen from low pressure tanks is compressed directly into the ship.

The advantage of this solution is that no high pressure storage is required, reducing the cost and complexity of the system.



Schematic diagram showing the principle of cascade filling

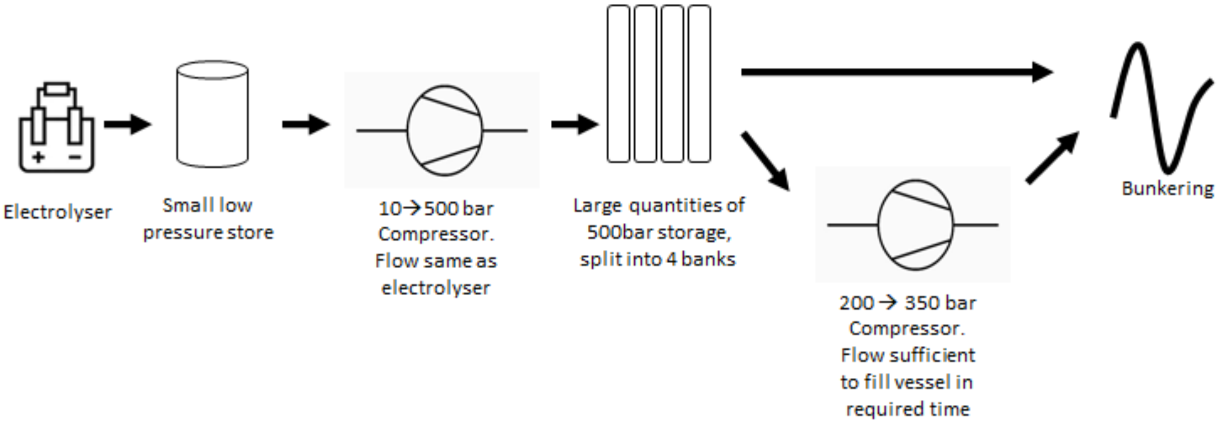
However, there are disadvantages of direct filling:

- In the simplest iteration, the ‘low pressure tanks’ are at the output pressure of the electrolyser. However, being at such a low pressure, this will require 30 times the storage volume. This is likely to be too high if space is a limiting factor. One possible solution for platforms and ports with limited space could be subsurface storage.
- This will require a compressor capable of accepting 10 bar input hydrogen and an output of gas at 350 bar, but with a flow rate designed to transfer all of the hydrogen to the ship as quickly as possible to minimise the bunkering time. Thus, direct filling requires a flow rate often 5 to 10 times faster than the compressor used for cascade filling, which can lead to a very high CAPEX.

Hybrid systems

To overcome some of the disadvantages of the cascade and direct filling systems, it is possible to have hybrid systems.

For example, it is possible to use cascade filling for the bulk of the hydrogen transfer, then top up with direct filling. Here, smaller cascade banks are used, so that they equilibrate below the desired level and when the cascade is complete, a compressor is used to directly fill the ship from the cascade banks for perhaps the last 100 bar, with a flow rate substantially lower than the pure direct fill.



A schematic diagram showing an optional ‘hybrid’ layout

Liquid Hydrogen Bunkering

Once hydrogen is generated as a low pressure gas, it is then liquefied (through cooling to -253°C at atmospheric pressure; a process which can consume 12 kWh/kg H2[1] , or up to 36% of the energy entrained in the hydrogen), The LH2 will be stored in vacuum insulated cryogenic tanks on the platform until ready for transferring to the ship. These tanks are designed to minimise the boil off gas such that <0.12% is lost per day, in line with IMO requirements for LNG[2] , with the boil-off gas fed back into the system and re-liquefied or used in a fuel cell to generate electricity.

The LH2 could be dispensed directly to the ship that requires refuelling or to a dedicated bunker vessel, which could then refuel ships. For the mechanics of offloading LH2, there is no distinction between final vessel and the bunker vessel[3] .

Once connected, the transfer will be undertaken via a vacuum insulated hose, complete with interlocks to ensure safe connection. However, it should be noted that these double metal walled hoses are not particularly flexible. Thus, the traditional method of pulling the hose to the vessel via a pilot line suspended from a boom over the ship, is likely to be impractical. However, if it is arranged, the hose will require a breakaway coupling, which will snap and seal both ends in the event that the ship and bunkering facility move too far apart.

Two suppliers, Man-Cryo and Cryostar, each have a different approach to LH2 bunkering and offloading, as described below.

Man-Cryo would install a small evaporator working against ambient air on the quay/ platform to produce a controlled amount of gaseous hydrogen. This gas is then used to pressurise the platform's LH2 tank and push the hydrogen to the ship. A typical set up for a small ship can transfer 4 tons of LH2 in about 1 hour, although this speed can be increased by using a wider diameter hose.

Cryostar would use cryogenic pumps to transfer the hydrogen to the ship, with the speed being varied by the capacity of the pump. While this method is simpler in terms of the process engineering, the CAPEX of the cryogenic pump is likely to be significant.

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[1] Provided in discussion with Cryostar

[2] Zakaria, Mohamad Shukri & Osman, Kahar & Musa, Md. (2012). Boil-Off Gas Formation inside Large Scale Liquefied Natural Gas (LNG) Tank Based on Specific Parameters. Applied Mechanics and Materials. 229-231. 690-694. 10.4028/www.scientific.net/AMM.229-231.690.

[3] This is notably different to a gaseous system, where if a bunker vessel were to be used with cascade filling, the storage on the bunker vessel would need to be at a higher pressure than on the ship. In turn, the platform would require storage at a higher pressure than on the bunker vessel

Containerised Refuelling

‘Containerised refuelling’ is a term used to describe the process of filling modules of compressed or liquefied hydrogen storage (usually in a 20-foot or 40-foot ISO frame) and then lifting them onto the vessel where they can connect into the ship’s fuel system. Bunkering therefore consists of lifting the empty storage container off the ship and replacing it with a full one.

Many companies, particularly those who manufacture frames of compressed hydrogen storage, are developing this concept, which has the following advantages:

- Bunker times are reduced, as fuelling takes the same time as loading and securing containers,
- For GH2, containerised refuelling overcomes the problem of an efficient way of transferring gas from the platform to the vessel.
- For LH2, it removes the requirement for a cryo-pump or tank that can self-pressurise to transfer the hydrogen to the ship. The LH2 can simply be generated, stored and physically lifted into position.

However, while appealing, there are the following substantial issues with containerised refuelling:

- Ownership and responsibility for equipment is not so clear. When multiple platforms owned by different operators are bunkering many vessels, the frames of stored hydrogen will be swapped many times between different platforms and ships. The owner will find it difficult to track their equipment, and harder to perform mandatory inspections. However, modern technology would facilitate this. A scenario could exist where the owners of the storage leased the equipment to the ship operators and platforms, who in turn checked them during refuelling using RFID, or similar technology;
- If ships are allowed alongside the platform for refuelling, there are considerable safety implications of using a crane at sea to lift a 40-foot frame filled with LH2 or GH2, swing it over the side of the platform and lower it onto the deck of a vessel which is likely to be rolling in the swell. Dropping a container onto the vessel deck (or another container), could result in a catastrophic release of hydrogen;
- If, as seems likely, an exclusion zone would be present around the platform to prevent impacts, this would result in the bunkering point being located at a substantial distance from the platform storing the hydrogen. It is unclear how the

fuel containers would be safely moved to the ship. Therefore, this solution is more suited to refuelling in a port rather than a platform;

- The repeated connecting and disconnecting of fittings on the ship or container would lead to wear and potential leakage;
- While swapping containerised hydrogen has been completed commercially on land, this has not been attempted in a marine environment. As such, a platform operating this method would be considered a pilot plant at TRL 5.

Further Information, Explanation and Methodologies

See Section 3 of Marinized Hydrogen in the North Sea Region full report.

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