POLICY BRIEF

12 August 2022

Interreg North Sea Region DUAL Ports

European Regional Development Fund

Marinised Hydrogen Technology

Introduction and Objectives

The development of hydrogen propulsion systems 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 an overview of hydrogen as an energy source for commercial shipping.

THIS BRIEF

1. **Identifies current hydrogen-propelled vessel projects globally;**
2. **Reviews the current state of onboard marinized hydrogen technologies in detail;**
3. **Establishes technology readiness levels (TRLs) for marinized hydrogen technologies.**

Review of Hydrogen-Propelled Vessel Projects

A review of over 60 hydrogen-related merchant ship projects was conducted from seagoing ships to small inland craft. More information on hydrogen-propelled vessels can be found in ZESTAs ShipZERO conference proceedings (ZESTAs, 2021a) and IEA Task 39: Hydrogen in the Maritime (MacLaine et al., 2021).

The approximate voyage distances of each vessel project, where known, are summarised in Table 1 below (a full list of vessels can be found in the Appendix). Where distances are known, they are given in nautical miles (nm). The majority of vessels operate in short routes or harbour areas.

Distance	Voyage summary	Number of projects
Long	Transoceanic	4
Medium	Short sea shipping and long inland routes	6
Short	Short inland routes and harbour operations	19

Table 1 – Summary of voyage distances of hydrogen-powered ships in the projects reviewed.

Ship type	Number
Passenger Vessels (all types and sizes)	16
Tourist Boats (all operating areas)	7
Inland Cargo Vessels	5
Research Vessels	5
Crew Transfer Vessels (CTVs)	3
Harbour Tugs	3
Inland Pusher Tugs	2
Water-taxis	2
Other	10
Total	**53**

*Table 2 – Ship types of hydrogen-powered ships in the projects reviewed.**

*"Other" ships types are 1 each of the following: Autonomous Underwater Vehicle, Container Vessel, Cruise Vessel, Jack-up Vessel, Narrowboat, Offshore Construction Vessel, Offshore Supply Vessel, Pleasure Yacht, Pure Car Carrier, Ro-Ro Cargo Vessel

Short-route ferries operating in national waters are the most common ship type for the following reasons:

- **Short, predictable routes:** Most of these ferries operate on routes that are usually less than 10 nautical miles long and often in protected waters such as natural bays or fjords. The influence of heavy weather is smaller than on open sea routes and thus the energy requirement can be determined with a high degree of accuracy.
- **Onboard space:** Due to safety regulations, passenger spaces are not permitted below the waterline. Thus, the hull below the main deck on most short-route ferries consists partially of unused void spaces, which can be used for hydrogen storage without increasing the vessel's size.
- **Low energy requirements:** Short-route ferries service speeds of are in the range of about 10 knots and the vessels make frequent stops and operation is often not continuous throughout the day. This allows for more frequent bunkering, hence, reduced storage space.
- **Regulation:** Ferries operating in national waters are usually regulated by a single flag state, therefore it is easier to bring into force new regulation or case-by-case approvals.

It is possible to power most ship types with hydrogen, if incorporated early in the design stage.

Photo: Ivan Østvik, Norled AS

Onboard Hydrogen Storage

Compressed (gaseous) and liquified (cryogenic) hydrogen are the two most widely adopted types of **Onboard Hydrogen Storage**. Metal hydrides have successfully been employed on hydrogen-powered submarines.

There are many factors that influence the choice between compressed and liquefied hydrogen storage onboard. Among the most important are:

- **Quantity of hydrogen** to be stored, mainly as a function of installed power (propulsion and/or auxiliary), load profile, sailing distance and operational/safety reserves;
- **Available space** for tanks
- **Bunkering** intervals, port infrastructure and available time for bunkering operations;
- **Economics:** cost of gaseous vs. liquified hydrogen fuel, equipment, and infrastructure.

There is no simple answer, nevertheless, figure 2 gives a basic indicator.

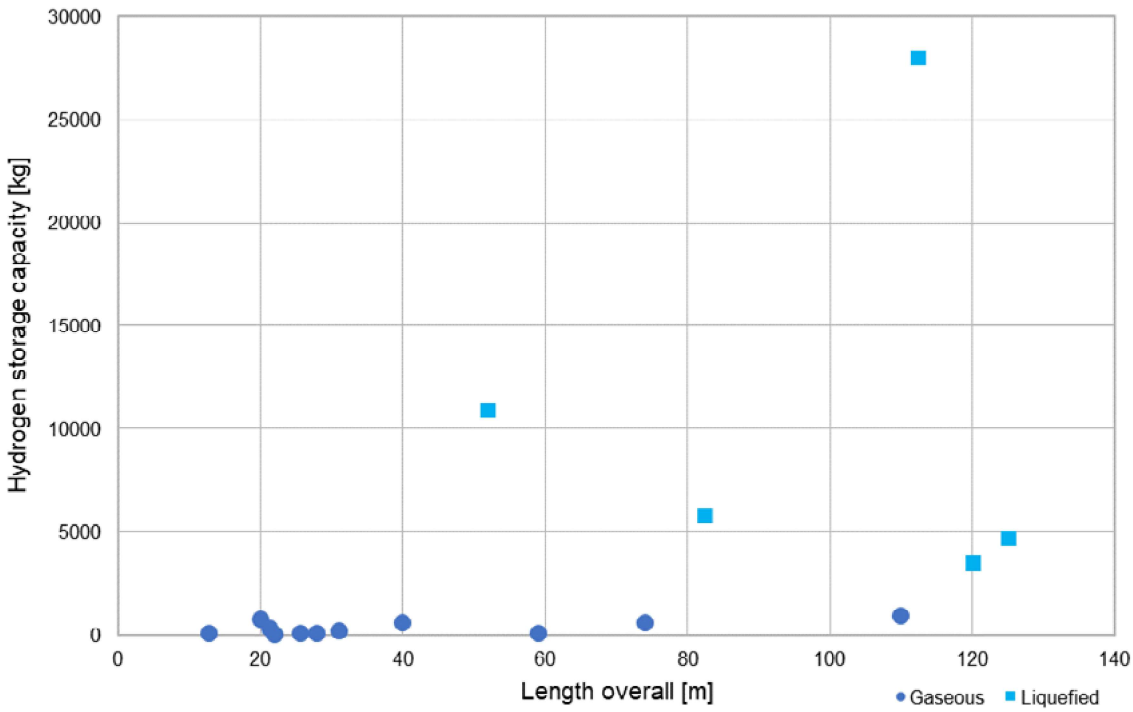

Figure 2 – Graph of Total Stored Energy, E, over Length Overall, LOA, for hydrogen vessel projects reviewed.

This compares onboard hydrogen storage capacity and vessel length. Hydrogen storage capacity is the basis for the space required onboard, regardless of vessel type, operation and size. Ship length is a suitable indicator of weight, volume and onboard space. These are parameters that can be found on all ship types.

Compressed gaseous hydrogen

Hydrogen is generally stored at 350 bar or 700 bar. Compression to 350 bar requires using 6% of the hydrogen's energy content, while 700 bar requires 11%. The equipment and processes are TRL 9.

Generations of tanks used for compressed hydrogen are subdivided into the following types:

- **Type I**: Steel/aluminium gas cylinders similar to those for any technical gas, with storage pressure 250-300 bar;
- **Type II**: Aluminium cylinders with filament windings as reinforcement wrapped around them. The fibres can be made of glass, carbon or aramid. Storage pressure 250-300 bar;
- **Type III**: Composite tanks made of fibre-reinforced polymers with an inner metal liner. Storage pressure up to 700 bar;
- **Type IV**: Composite tanks made of fibre-reinforced polymers with an inner polymer liner. Storage pressure up to 700 bar.

The more advanced the tank, the lighter they are in comparison to the hydrogen fill that they can hold.
Compressed hydrogen tanks planned for use on ships were found in capacities up to 1,500 litres, corresponding to close to 28 kg of hydrogen capacity.

Liquefied hydrogen

The boiling/liquefaction point of hydrogen is -253°C. Liquefaction requires up to 30% of the hydrogen's energy content. All components in contact with liquified hydrogen must be thermally insulated and made of materials suitable for cryogenic applications, such as austenitic steels.

Tanks for liquefied hydrogen are similar to LNG tanks, the main difference being the much lower storage temperature and material compatibility for hydrogen. Despite careful insulation, the tank slowly absorbs heat from its environment and part of the liquid inside evaporates, known as "boil-off". Therefore, tanks are designed to withstand pressures of 5-10 bar.

Pipes for transport of liquid hydrogen are double-walled vacuum-insulated pipes. Special cryogenic pumps exist for moving liquid hydrogen in large quantities. To supply hydrogen to fuel cells or engines, it is brought to a gaseous state using a vaporizer, as with LNG.

Hydrogen fuel cell propulsion and liquefied storage is installed on the Norwegian RoPax vessel Hydra, operated by Norled to carry 300 passengers and 80 cars (ZESTAs, 2021b).

A liquefied hydrogen tanker, Suiso Frontier, with a cargo tank capacity of 1250 m3, was launched in late 2020 (Kawasaki Heavy Industries Ltd., 2020). Kawasaki Heavy Industries has received Approval in Principle (AiP) from ClassNK for a larger announced plans for a 160,000 m^3 capacity tanker, expected in the mid-2020s. The vessel will be fitted with four 40,000 m^3 tanks containing 10,000 tons of hydrogen in total (Kawasaki Heavy Industries Ltd., 2022).

Sodium borohydride

Sodium borohydride (NaBH4), a granular solid metal hydride, can be used as a hydrogen carrier. It enables much simpler storage and handling of hydrogen. When catalysed, it releases hydrogen, heat and the reaction by-product, sodium metaborate (NaBO2) which can be reused for further storage cycles (ZESTAs, 2022).

Space for hydrogen storage

There is no current specific international regulation for hydrogen as fuel onboard ships. Therefore the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels, or IGF Code, is used for guidance.

The IGF Code states that boundaries of tanks carrying liquified gas should have a certain minimum distance from the outer shell, as a measure to prevent tank damage following a collision. A minimum distance of at least 0.8-2.0 m (depending on ship dimensions) has to be kept in any case.

Vessels that are designed with large void spaces below deck have an advantage for fitting hydrogen storage over vessels where these spaces are all occupied.

These include (non exhaustive):

- Short-route ferries
- Large passenger and vehicle ferries
- Offshore construction vessels
- Deadweight carriers, e.g. ore carriers
- Harbour tugs

Hydrogen tanks may also be fitted on deck, if sufficient area is available. Installations on deck are enclosed cabinets or containerized. The advantage of an installation on the open deck is the natural ventilation and reduced risk associated with hydrogen leakage and fire hazard. An installation below deck in enclosed spaces requires more onerous ventilation, leak detection, alarm, and fire prevention measures.

Propulsion

Hydrogen fuel cells generate electricity, therefore propulsors are driven by electric motors. Fuel cells are always complemented by electric battery arrays, known as energy storage systems (ESS). The ESS provides power when the fuel cells are not operating, supplies short-term power demand peaks (so-called "peak-shaving"), supplies power during transient loads and can reduce the total installed power required from the fuel cells.

Where hydrogen-fuelled engines are used, propulsion can be either mechanical using the engines as prime movers, turning propellers or, driving generators to power an electric propulsion plant as described above.

Fuel cells

Marinized proton exchange membrane (PEM) fuel cells are a mature, commercially available technology (TRL 9). Marinized solid oxide fuel cells (SOFC) have been tested onboard a ship (TRL 7) at the 100 kW scale (Bianchi & Bosio, 2021).

There are over eight PEM fuel cell manufacturers worldwide producing commercially, with claimed lifetimes of 20 years stated. Outputs range from 0.5 to 1,200 kW (1.2 MW). Modules can be combined to achieve up to 6 MW. The maximum reported PEM efficiency is 58% and averages at around 50% among the various modules on the market, typically occurring at part load. PEM fuel cells are always supplied with gaseous hydrogen. If liquefied hydrogen is used, a vaporiser is needed.

The exponential increase in PEM fuel cell power output of the projects reviewed is shown below, with tens of MW expected before 2030 (order of magnitude of conventional marine engines). At least one multi-MW vessel is under construction.

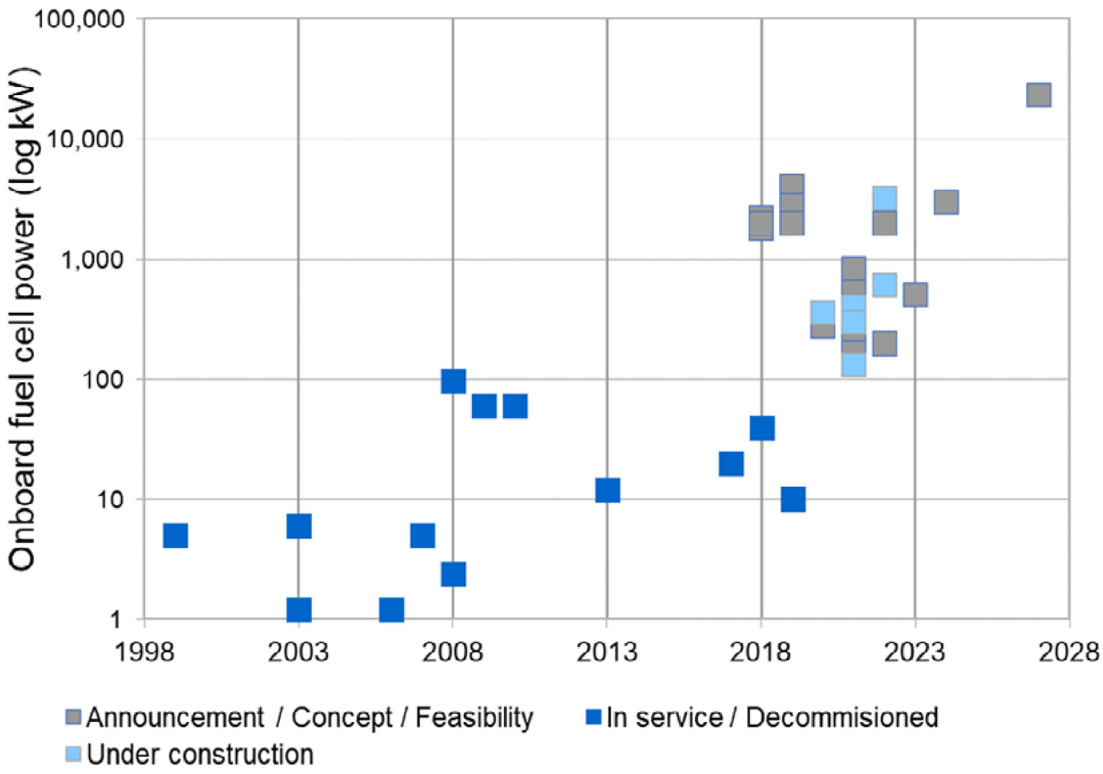

Figure 3 – Graph of total installed hydrogen fuel cell power (in logarithmic scale) of individual ship projects over years.

Hydrogen-fuelled internal combustion engines (ICE)

Presently, this technology is being scaled up for engines in the 2-3 MW range with the engines burning up to 85% hydrogen and 15% diesel fuel (Anglo Belgian Corporation nv, 2022). Two operational dual-fuel hydrogen-diesel ICE passenger vessels Hydroville and Hydrobingo are currently operating using compressed gaseous storage (CMB-Tech, 2022).

However, this is not an emission-free technology. Since the hydrogen is combusted, the engine is impurity-tolerant, steam reformed hydrogen from natural gas (SMR), so-called 'grey hydrogen', can be directly used. In addition nitrogen oxides (NOx) are emitted during combustion due to high temperatures and pressures. If fuel oil is used as pilot fuel to ignite the hydrogen, pollutants including CO2, NOx, sulphur oxides (SOx) and particulate matter (PM) will be emitted.

Hydrogen-fuelled gas turbines

Although no ship project using hydrogen-fuelled gas turbines was found, they might at some point play a role in some very specific applications such as large fast ferries or other applications where power density is critical. Gas turbines partially fuelled with hydrogen mixtures exist and burning pure hydrogen is being researched (Access Intelligence LLC, 2019).

Further Information, Explanation and Methodologies

See - Marinized Hydrogen in the North Sea Region full report

For more details of onboard hydrogen technology systems, see Section 6, for safety considerations, see Section 7.

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Appendix: Overview of routes and operating areas of hydrogen-powered ships in reviewed projects

Distance	Route or operating area	Project name & ship type
Long	Worldwide, including polar navigation	MARANDA Aranda
	Worldwide, excluding polar navigation	Energy Observer, Race for Water
	Transatlantic	Lateral Engineering AQUA
	USA Coasts	Zero-V
Medium	Baltic Sea, unspecified location	Samskip SeaShuttle
	Norwegian West Coast	Havila Kystruten FreeCO2ast, HyShip Topeka
	Oslo–Frederikshaven–Copenhagen	DFDS Hydrogen Ferry
	Trondheim–Kristiansund, NO	Rødne E-Maran
	Rhine River, unspecified location	Future Proof Shipping Inland Vessel
	Hamburg–Berlin, DE, and other inland routes on rivers Havel, Spree and Elbe	Elektra Inland Pusher Tug
Short	Antwerp–Kruibeke, (4 nm), BE	Hydroville
	Alster River, Hamburg, DE	Alsterwasser
	Mittelplate Oil Field, Wadden Sea, DE	Coastal Liberty
	Rhine River, Bonn Area, DE	Hydra
	Nantes, FR	Navibus Jules Verne 2
	Rhône River, Lyon area, FR	Flagships Pusher Tug
	Kawasaki Port, JP	e5 Tug
	Yokohama Port, JP	e5 Tug, Yokohama Tourist Ship
	Amsterdam, NL	Nemo H2 Inland Tourist Boat
	Amsterdam–IJmouden, NL	H2Ships Tourist Boat Havenbeheer
	Delfzijl–Rotterdam, NL	FELMAR Antoine
	Finnøy-Route: Fogn–Judaberg–Nedstrand–Jelsa, NO	Norled Finnøy H2 Ferry Conversion Hidle
	Hjelmeland–Ombo Skibaviga–Nesvik–Hjelmeland (7 nm), NO	Norled Rogaland Liquid H2 Ferry Hydra
	Valestrand–Breistein (1.5 nm), NO	Osterøy Ole Bull
	Kirkwall–Shapinsay (4 nm), UK	HySeas III
	Bristol, UK	Passenger Ferry Hydrogenesis
	UK canals	Narrowboat Ross Barlow
	San Francisco Bay, USA	Duffy-Herreshoff DH30 Water Taxi, Water-Go-Round
	Harbour service, unspecified location	OSD IMT H2 Harbour Tug

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