El Hidrógeno como Combustible Marino y los desafíos de la Descarbonización

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18 March 2025

Introduction to Hydrogen systems

Agenda

1. Why use Hydrogen as marine fuel?
2. Hydrogen Properties
3. Design challenges
4. Design Considerations
5. Approval framework
6. Hydrogen Situation today

Why use Hydrogen as marine fuel?

Hydrogen as marine fuel

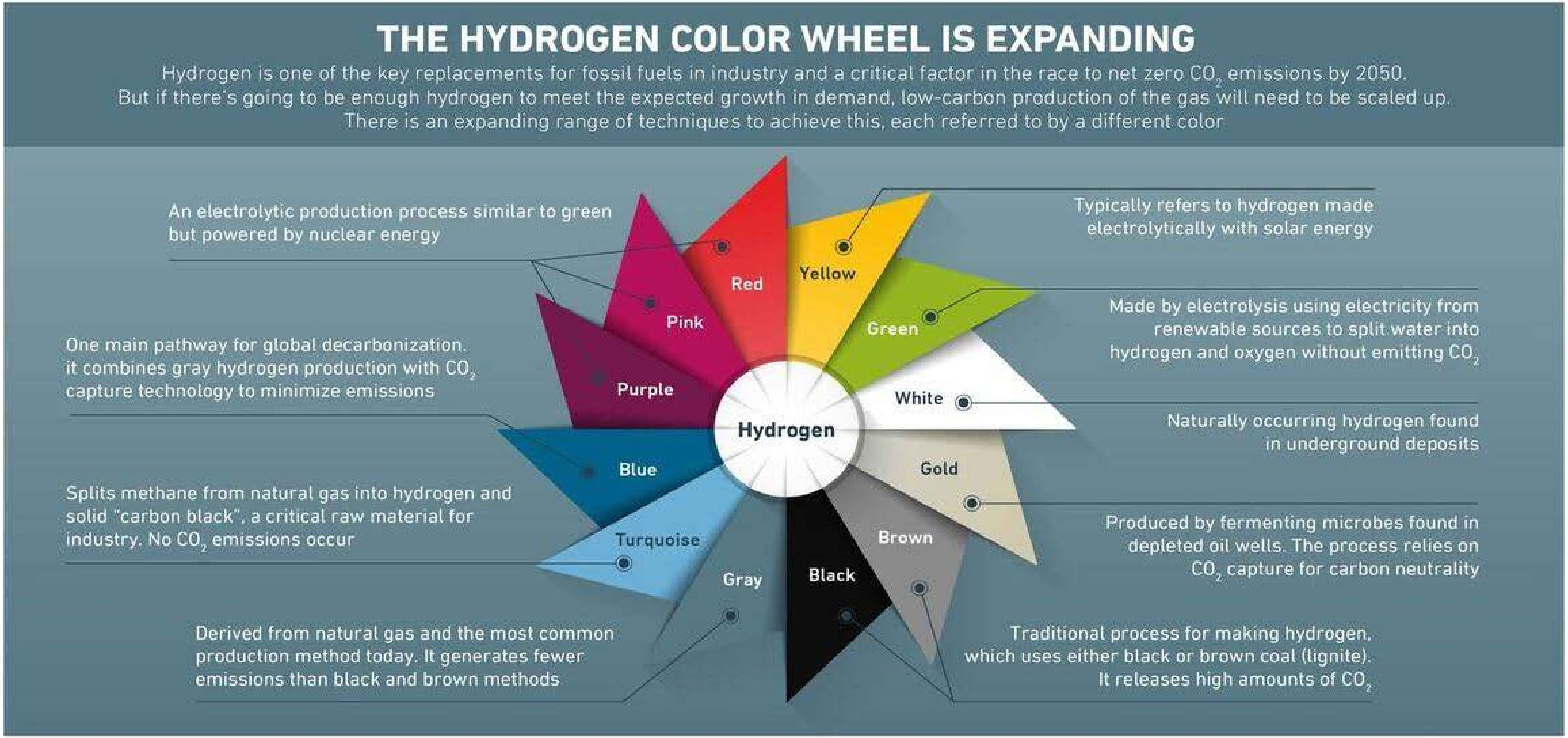
- **IMO strategy –** Shipping contributes 3% of all greenhouse gases worldwide. IMO’s objective is to reduce GHG emissions from international shipping by at least 50% from 2008 levels by 2050
- **Decarbonization –** Alternative and zero carbon fuels offer a pathway to achieve this goal
- **Challenges –** Toxicity of Ammonia, limited availability of biofuels, large and heavy batteries for long distance shipping etc.,
- **Solution -** Hydrogen is a potential zero-emission fuel alternatives capable of meeting shipping industry’s energy needs

Hydrogen as marine fuel

- **Production –** Green hydrogen by electrolysis using renewable sources, blue hydrogen from captured carbons/hydrocarbons, grey hydrogen from hydrocarbons using non-renewable resources, White hydrogen from natural reserves
- **Storage options –** Compressed gas, Liquified gas, metal hydrides, organic hydrides
- **Propulsion methods –** Combustion engines (e.g., ICE, GT), Fuel cells (e.g., Proton exchange membrane, Solid oxide etc.,)

Hydrogen as marine fuel

- **Challenges –** Safety, material compatibility, low volumetric energy density, regulations, scaling up from land-based applications, limited industry knowledge/experience
- **Early applications – As fuel:** Tugboats (Hydro tug), Passenger ferries (Torghatten Nord), Cruise ships (Viking), Bulk carriers (With Orca), **As cargo:** LH2 carriers (Suiso Frontier) etc.,
- **Regulatory framework –** Progress on draft rules for hydrogen as fuel based on IGF code (LR published ruled for hydrogen as fuel), IMO interim recommendations for carriage of Liquid hydrogen as cargo(based on IGC code), Approval of Alternative design and arrangements



MOVE THE WORLD FORW>RD MITSUBISHI HEAVY INDUSTRIES GROUP

Hydrogen Properties

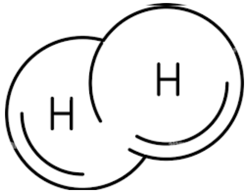
Gaseous hydrogen properties

Highly Flammable

Can burn from 4% to 75% v/v in air when ignited

Low volumetric Energy density

Need to be stored at high pressures

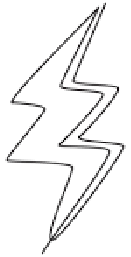


Small molecular size and low density

Extremely high potential for leaks and fast dispersion

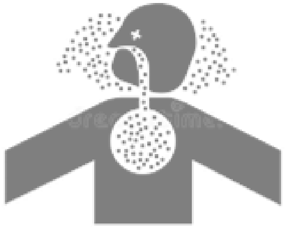
Colorless, odorless gas, with near invisible flame

Difficult to detect combustion



Low minimum ignition energy

Can ignite by electrostatic discharge

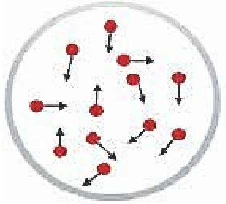


Asphyxiant, non-toxic, non-corrosive

Liquid hydrogen properties

Low temperature

At -253^{0}C, nitrogen and oxygen will freeze



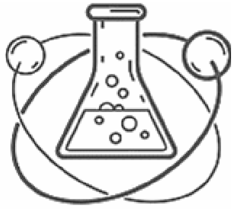
Low density

Difficult to pump; high pressures required for flow

Low heat of vaporization

High vaporization rate if not well-insulated

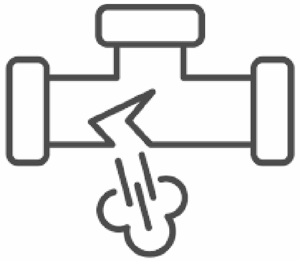
(it requires very little energy to change from liquid to gas)



Energy intensive liquification

Consumes more than 30% of hydrogen's energy content

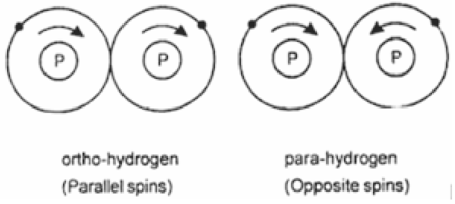
(Liquefaction processes are not very efficient)



High liquid to gas expansion

850x increase in pressure during evaporation

(it expands by a large factor in terms of volume)



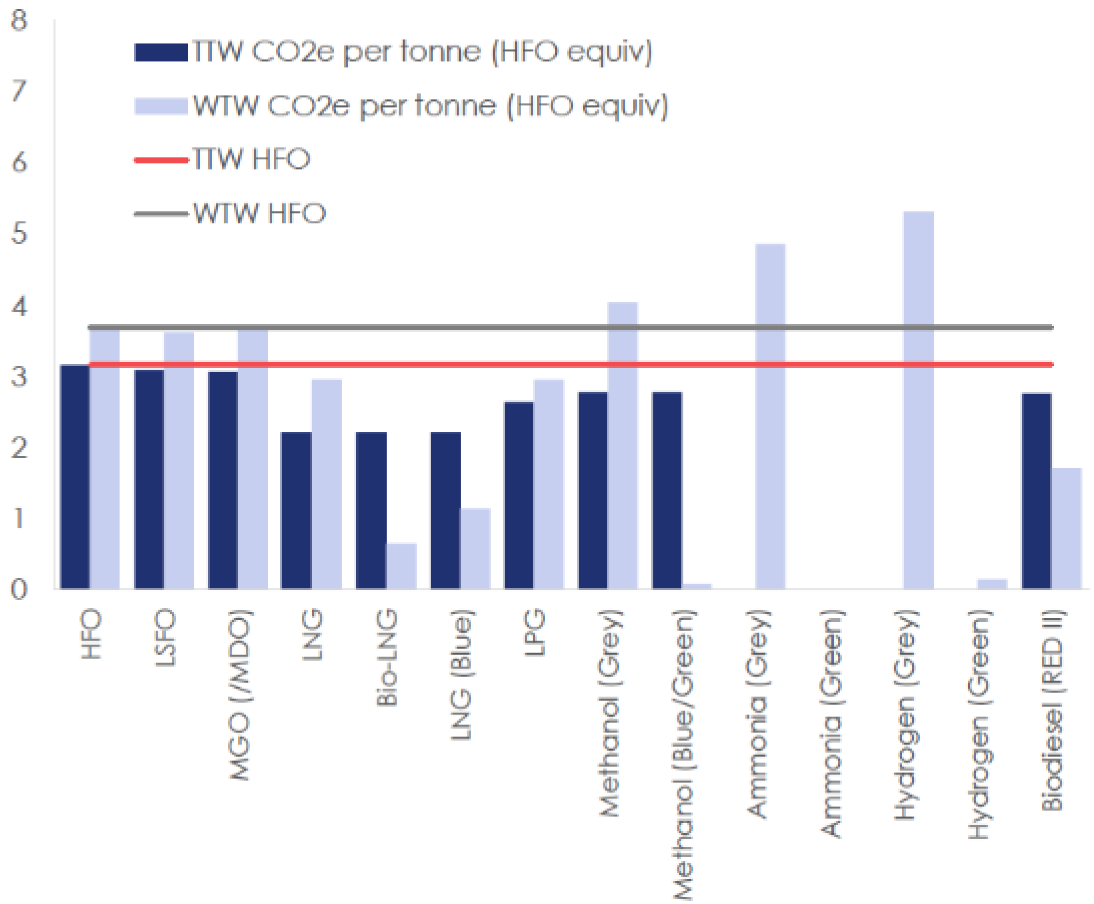
Ortho-Para conversion

Exothermic reaction, results in evaporation

Hydrogen Characteristics

Emission factors

Tonnes Of CO2 Eq. per Tonne Of HFO Equivalent Fuel Consumption



	Ship Emissions	*Comparison <- // ->*	Global Lifecycle Emissions
	TTW vs HFO	WTW vs TTW	WTW vs HFO
HFO	100%	+17%	100%
LNG	70%	+34%	80%
Bio-LNG	70%	-71%	18%
LNG (Blue)	70%	-48%	31%
LPG	83%	+12%	80%
Methanol (Grey)	88%	+45%	109%
Methanol (Green)	88%	-97%	2%
Ammonia (Grey)	0%	High WTW	132%
Ammonia (Green)	0%	No WTW	0%
Hydrogen (Grey)	0%	High WTW	144%
Hydrogen (Green)	0%	Very low WTW	4%
Biodiesel (RED II)	87%	-39%	47%

Design Challenges

Challenges in Hydrogen systems design

Material compatibility

- Embrittlement
- hydrogen attack at high temperatures
- Permeable through composites

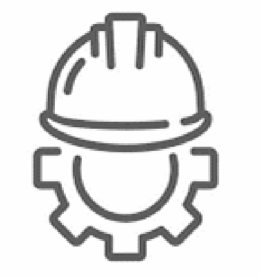
Design for high pressure

- 35-70 Mpa compressed hydrogen storage
- Pressure vessel and piping failures
- High energy explosions

Combustion and explosion hazards

Difficult to detect and extinguish hydrogen flames with conventional methods

Challenges in Hydrogen systems design

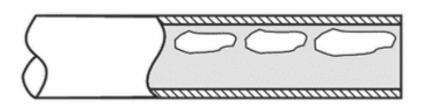


Design for safety

- Inherently safe designs
- Safe venting of hydrogen
- Inerting and ventilation
- Hazardous zones

Low temperature design

- Strict material requirements
- Thermal fatigue
- Insulation and vacuum systems

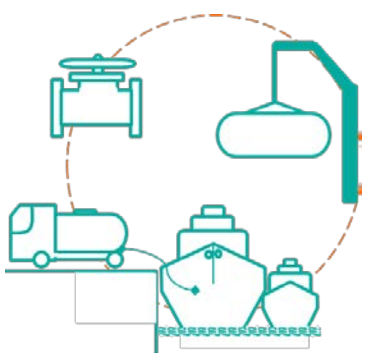


Two phase flow

- Eliminating cavitation
- Sloshing
- Stratification
- Geysering effects

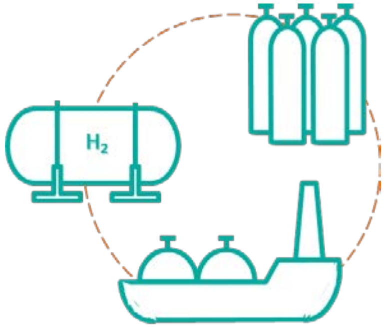
Design Considerations

Main hydrogen systems on ships



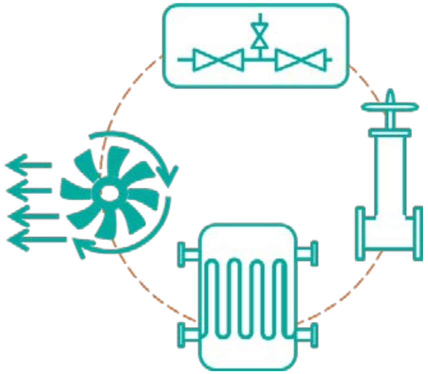
Bunkering systems

Shore-ship / ship-to-ship /Portable tanks,
bunkering valve manifolds onboard



Hydrogen containment

High pressure composite cylinders,
liquid hydrogen tanks



Fuel preparation room

Valve manifolds/cold boxes,
high pressure piping and components,
space ventilation

Fuel consumption room

Fuel cell room / engine rooms,
battery systems, hydrogen piping,
exhausts, ventilation

Design considerations for Hydrogen systems

Risk elimination and Inherently safe design
Fail-safe designs, design for worst case scenarios, safety devices, control and emergency shut down, hazardous area classification

Consequence management
Control of handled hydrogen quantity, detection, fire fighting systems, limiting personnel, safety cases, explosion analysis

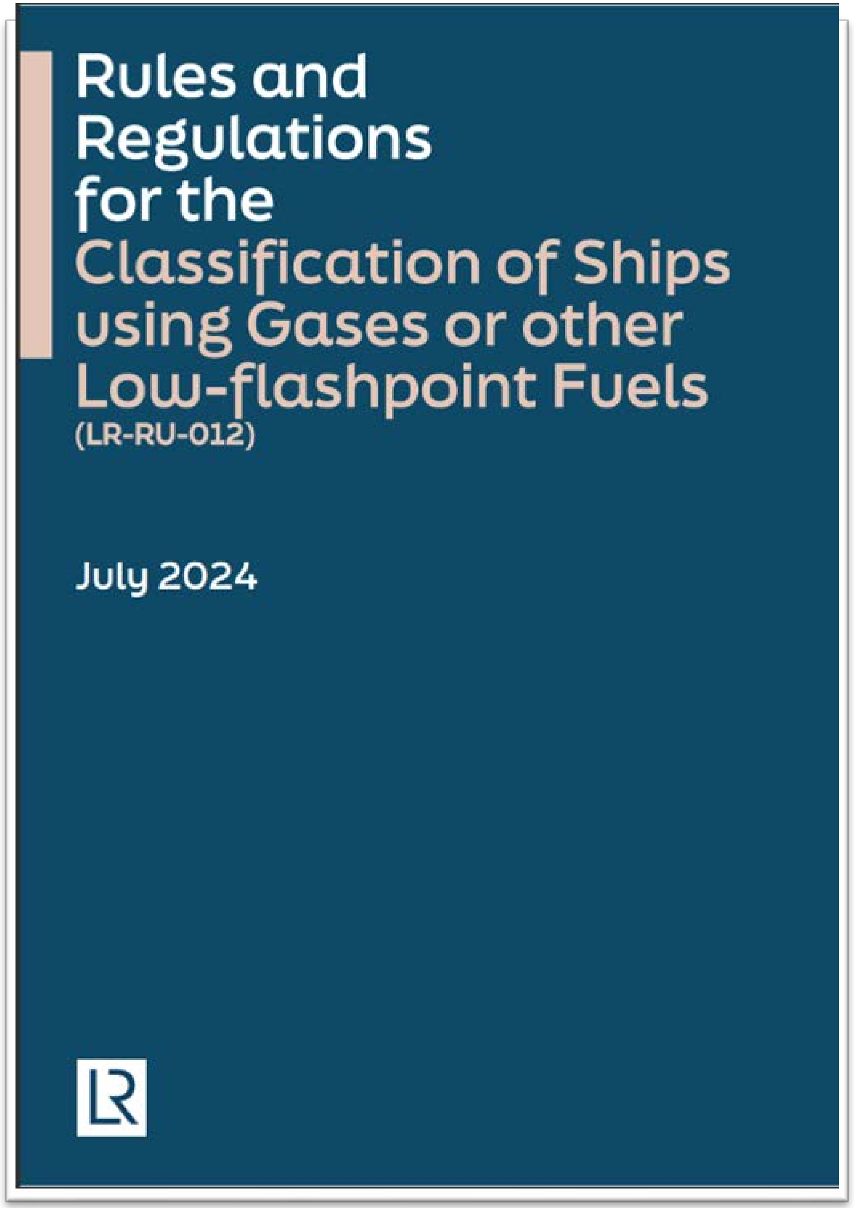
Commissioning and factory acceptance
Quality assurance plan, Workmanship, Survey procedures, traceability, review of commissioning trials

Inspection and Periodic maintenance
Preventive maintenance plan, replacement philosophy, maintaining logs, review of performance and functional tests

Operating procedures
Normal and emergency response manuals, trained personnel, periodic review of procedures

LR approval framework for alternative fuels

LR's rules for Hydrogen systems


Rules and Regulations for the Classification of Ships using Gases or other Low-flashpoint Fuels
(LR-RU-012)

July 2024

Appendix LR3 – Requirements for Ships Using Hydrogen as Fuel.

- Rules introduce the requirements for the **use of hydrogen as a fuel on board LR classed ships other than gas carriers**
- Requirements for the **arrangement, installation, control and monitoring of machinery, equipment and systems using hydrogen fuel (in both gaseous and liquified forms)** to minimize the risk to the ship and its crew.

https://www.lr.org/en/knowledge/lloyds-register-rules/rules-and-regulations-for-ships-using-gases-or-low-flashpoint-fuels/

Process for Hydrogen

Rules and Regulations for the Classification of Ships using Gases or other Low-flashpoint Fuels

Appendix LR3

- In April 2023, LR published the **world's first** maritime rules covering hydrogen as a fuel.
- They fill a gap within IMO's IGF Code.
- It has been drafted to maintain consistency with Appendix LR1, which addresses methanol or ethanol, and Appendix LR2 on ammonia as fuel.
- The hydrogen appendix enables designers to **understand the performance they must achieve** to ensure that a vessel will operate safely and reliably on hydrogen fuel, **either in liquefied or gaseous** form.

Process for Hydrogen

Rules and Regulations for the Classification of Ships using Gases or other Low-flashpoint Fuels

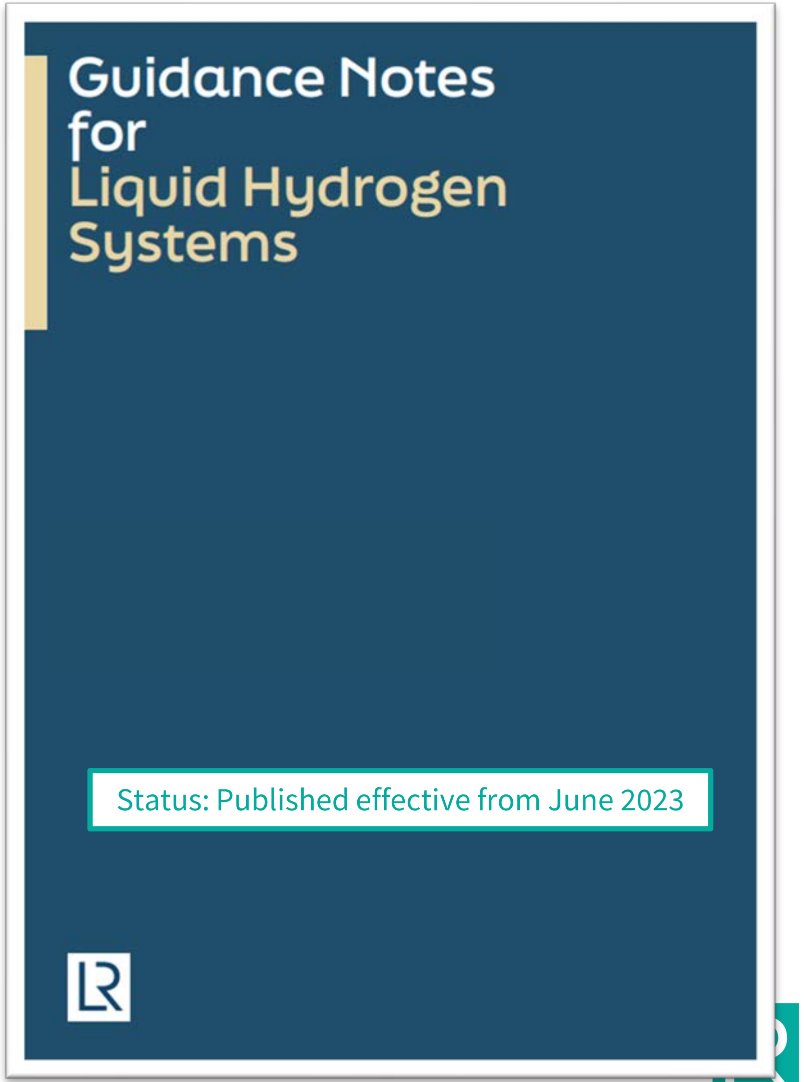
Appendix LR3

- Ships complying with the requirements of Appendix LR3 will be eligible for assignment of the **LFPF(GF,HY)** notation
- Hydrogen-ready Notation also available for ships built with conversion in mind
- Ships complying with the requirements of Appendix LR3 **in preparation to be fuelled by hydrogen** will be eligible for assignment of **descriptive notes**
  - **GR(AM,A): Approval in Principle**: compliance demonstrated for all systems
  - **GR(AM,S): Structural Reinforcement** Installed: required to support the proposed fuel tanks
  - **GR(AM,T): Tank** installed: tank design and related arrangements approved
  - **GR(AM,P): Piping** installed: piping system design approved
  - **GR(AM,E): Equipment** and **machinery** installed

LR's guidance notes for liquid hydrogen systems

https://www.lr.org/en/knowledge/lloyds-register-rules/guidance-notes/guidance-notes-for-liquid-hydrogen-systems/

- Objective
  - Design, arrangement, commissioning, qualification, in service inspection and maintenance of liquid hydrogen systems
  - Derived from the best practices and industry standards of aerospace, automotive, and cryogenic industries
  - Aimed at ship owners, operators, shipyards, equipment manufacturers, and suppliers of liquid hydrogen systems for marine applications
- **Material selection criteria** and testing requitements
  - Suitability table for commonly used materials (metallic and non-metallic) with gaseous and liquid hydrogen
- Design, selection, factory acceptance criteria, in-service inspection & maintenance of **piping components and pressure relief devices**
- Design, construction, and qualification of liquid hydrogen **tanks and piping**
- **Vacuum systems** design and measurement
- **System layout** for physical arrangement of piping & hoses, component placement, Tank connection space
- Installation and **Integration** Onboard



LR Rules for Hydrogen Fuel

Appendix LR3

- As an **example of a hydrogen-specific requirement**: a section about bunker stations, which are based on those for LNG bunkering safety requirements.
- Only the **additional hazards** related to handling hydrogen are covered in the new appendix, which states that "the *bunker station shall be located on the open deck with minimal congestion and with an unobstructed dispersion path for reasonably foreseeable leakage scenarios*."
- Other requirements include **identifying leakage scenarios** as part of an explosion analysis and to "identify, detail and justify the environmental and arrangement factors" relevant to each scenario
- LR's new rules are equally relevant for **fuel-cell installations and hydrogen used in internal** combustion engines
- LR's rules reflect the risk-based approach and support the LR risk-based design process and flag administration acceptance of the 'Alternative Design' process, to permit the use of hydrogen as a fuel.

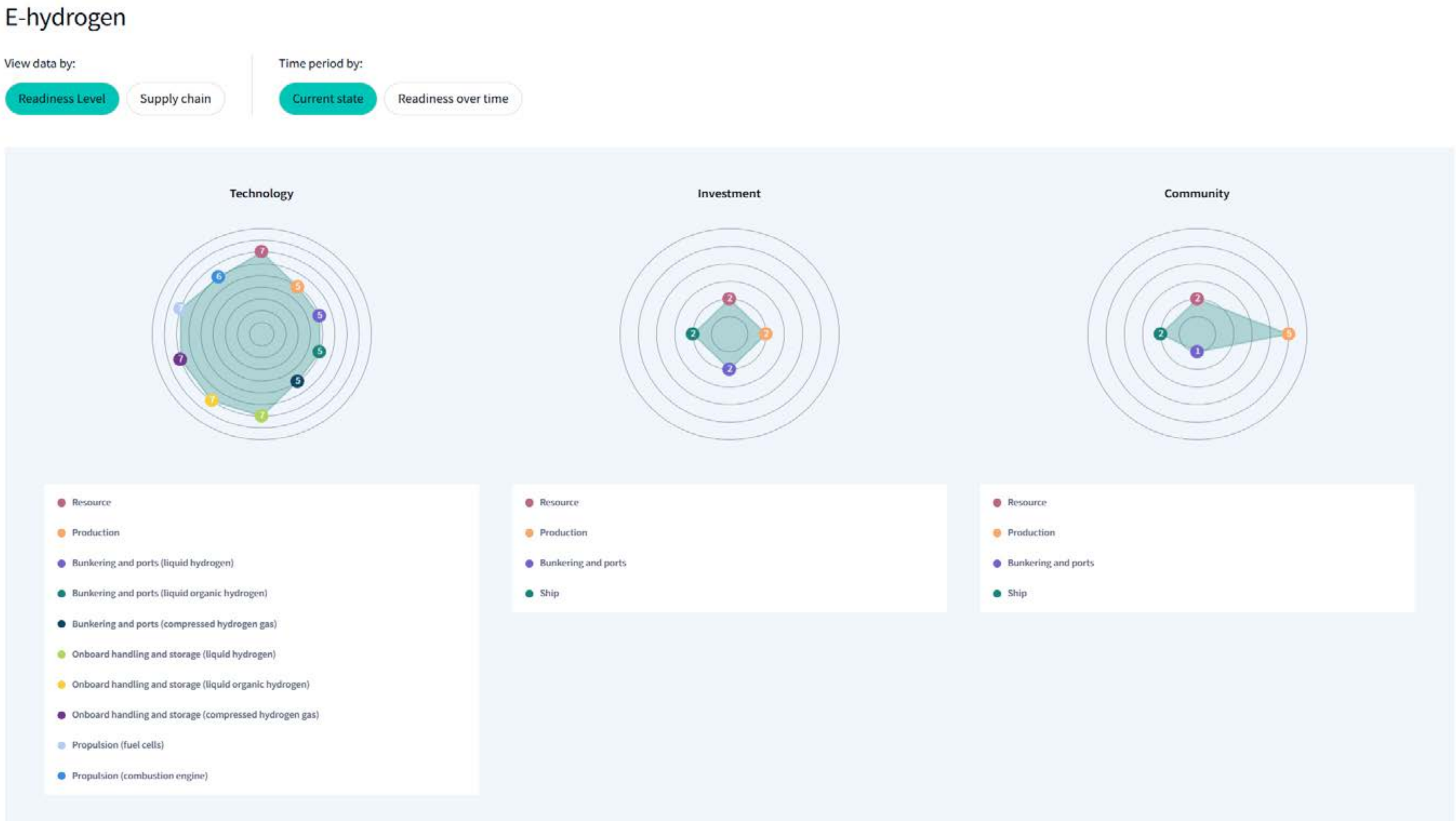
Hydrogen
Situation today

Readiness Levels

Technology, Investment and Community Readiness Levels

Combining

- **blue** hydrogen (NG and CCS) and
- **green** hydrogen (produced by electrolysis and renewable energy)



Readiness Levels

Technology, Investment and Community Readiness Levels

E-hydrogen

View data by:

Readiness Level | Supply chain

Time period by:

Current state | Readiness over time

Readiness Levels

Technology, Investment and Community Readiness Levels

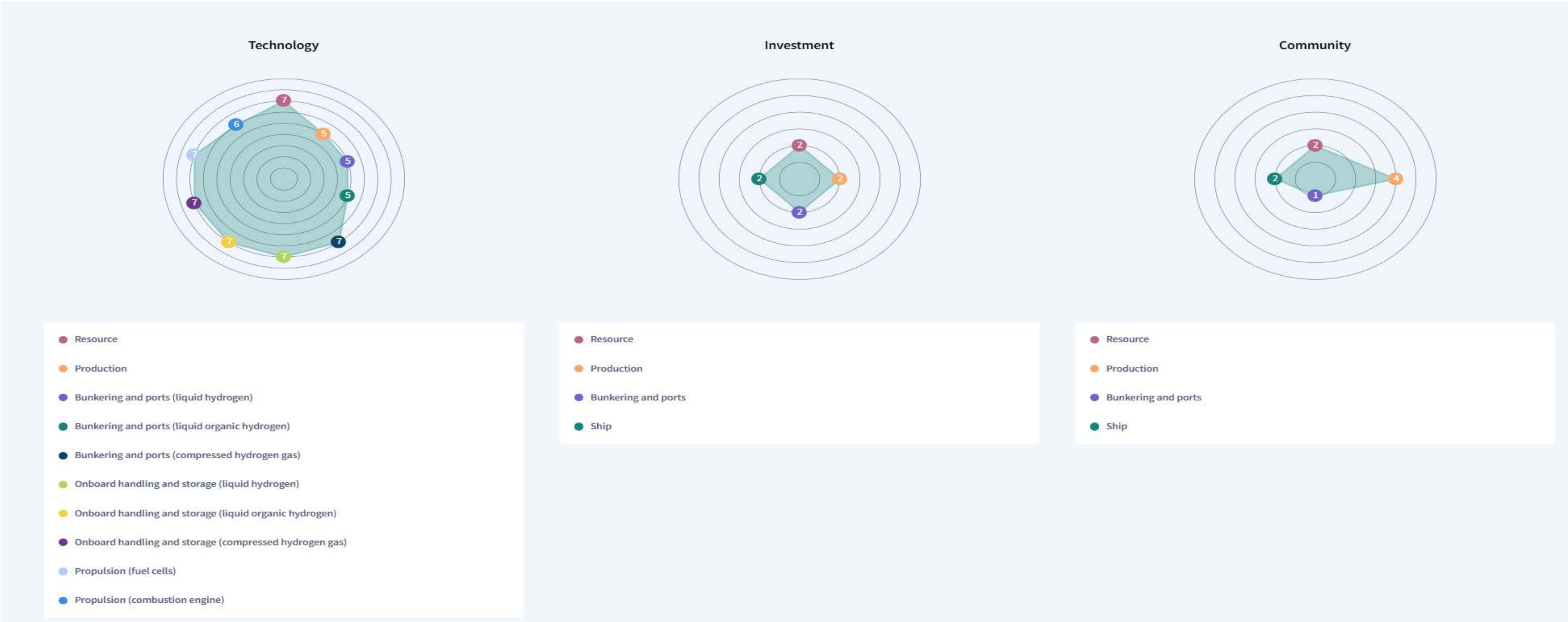
Blue hydrogen

View data by:

Readiness Level | Supply chain

Time period by:

Current state | Readiness over time



Hydrogen
Technical aspects

Technical suitability

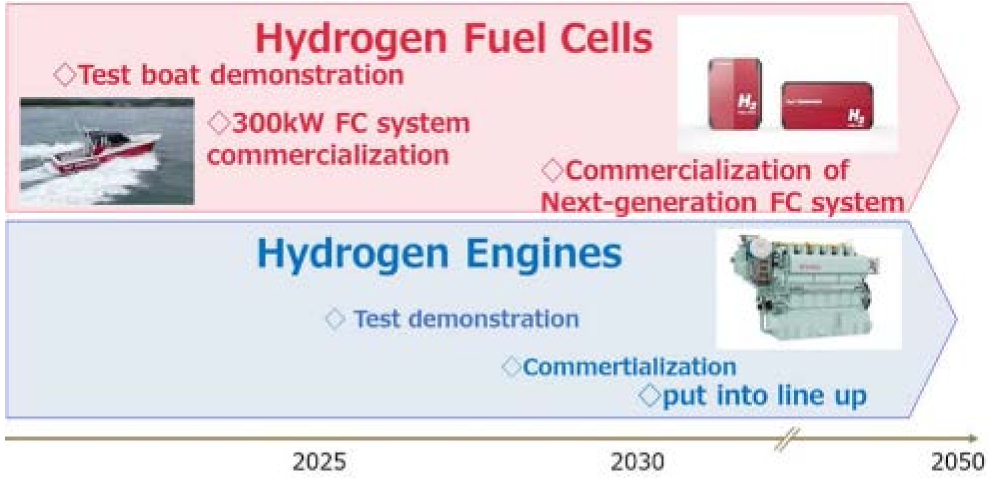
Overview

Internal Combustion Engines

- For the next years, hydrogen is likely to be used **for dual-fuel engines**. Hydrogen may be useful blended with ammonia.
- The fuel is at present **more commonly associated with 4-stroke** (medium/high speed) short-sea applications than with 2-stroke deep-sea applications. It is also where most of the projects and government funding currently are. *(source MAN ES)*

Fuel cells

- Hydrogen can be used with **different types of fuel cells** (Proton Exchange, Phosphoric acid, Alkaline types). Sometimes a gas reformer is needed as a pre-step.
- Some expect that fuel cells would ultimately replace diesel/DF generators.
- The volume of fuel to be stored for long distance shipping is the main barrier (loss of large cargo spaces for fuel storage).



Source: Yanmar Power Technology Co., Ltd.

Technical suitability

Internal Combustion Engine ICE

- Hydrogen has been **tested** in ICE years ago (invented in 1806) but is not widely used.
- H2 first used in diesel engines for buses
- Conventional DF engines could **be Tier III** compliant without SOx and CO2 emissions in the H2 phase.
- Hydrogen "**knocks**". It is easy to prematurely ignite H on engine hotspots.

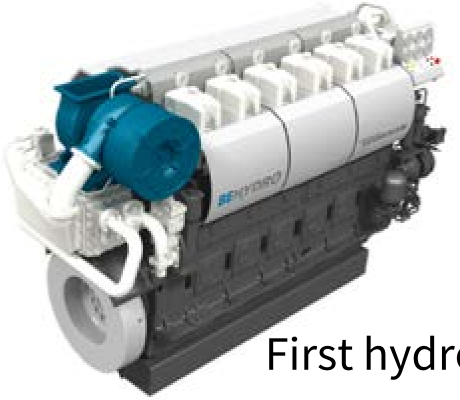
Fuel cells FC

- First FC were developed about **150 years ago**.
- Some **high temperature** FC (500°C) are able to **reform** their feedstocks, creating H2 from methanol, ammonia and LNG within the cell itself (internal reforming).
- **Low temperature** FC (200°C) use water-based electrolytes and require **high purity (99%) hydrogen** as fuel. Electrical efficiencies are lower.
- Fuel cell stacks have a **lower lifetime** than ICE.

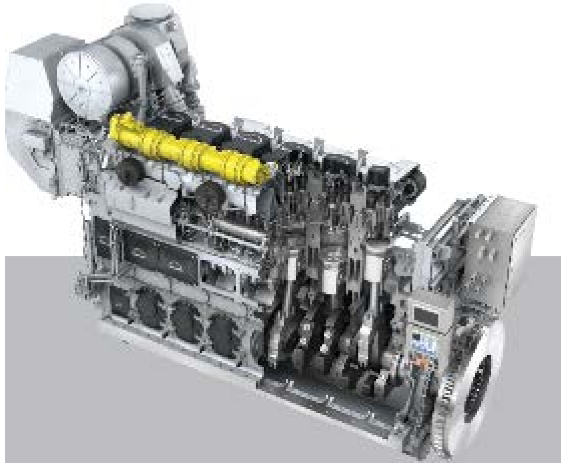
Source: SGMF Guide on Hydrogen An introduction; MAN ES Guide on Hydrogen

Technical suitability

ICE Engine



First hydrogen dual-fuel engine, BeHydro ©



MAN ES H2 engine concept based on DF engine

Fuel Cells

SGMF Guide – Fuel cells

FCwaveTM Fuel cells (Source: Ballard)

300kW-class maritime hydrogen fuel cell system
Credit: Yanmar ©

Technical aspects

Key elements considered for statutory and class compliance

- Fuel storage
- Onboard arrangements
  - Fuel preparation room
  - Fuel Gas Supply System (FGSS) and Fuel piping
  - Ventilation
- Fire detection and control

MAN Cryo
LH2 fuel gas supply system and vacuum insulated multilayer storage tank for marine applications

Fuel storage and containment

- Risk is significantly reduced via a **sound and reliable tank design**
- Current industry practice include the use of small scale **gaseous** hydrogen tanks – "off the shelf solutions" : land based design used for marine applications

- For **liquefied** hydrogen, cryogenic liquid tanks as IMO Type C tanks, with a crucial selection of materials:
  - Typically 3 layers:
    - Inner vessel: subject to material embrittlement
    - Insulation layer: Temperature maintenance layer
    - External Jacket: General tank protection layer
- Suiso Frontier is world's first liquefied hydrogen carrier, using Type C tank

NB: Land based LH2 tanks are not designed as per IMO codes criteria.

Double-wall stainless steel tank With a layer of vacuum insulation between the inner and outer shell

Kawasaki yard – Credit SIGTTO

Technical aspects

Onboard arrangements

- **Fuel systems**
- H_2 can **chemically impact austenitic stainless steel** (hydrogen embrittlement), so need to use the correct material, from pressure gauges or even thread seal tapes, to complex machinery parts.
- Constructions materials will need to be **compatible with low temperatures**. All piping needs to be vacuum insulated.
- Asa principle, liquid hydrogen should be **handled as little as possible** as any transfer provides opportunities for heat ingress and therefore vaporisation.
- **Boil-off rates** are high because of very low temperatures (0.3% per day).

Technical aspects

Safety arrangements

Leakage management

- Conceptually similar to LNG. But it is considered that hydrogen leaks will **never be eliminated**, only minimized. Rotating equipment can especially be difficult to make leak tight. The important criteria is **where to accept leaks** and where they can be eliminated.
- On a ship, free ventilation and dispersion is impossible. **Forced ventilation systems** required, and possibility to inert spaces where hydrogen may congregate.
- **Secondary barriers** required for insulation and for leak detection and monitoring.

Flammability risks

- Hydrogen fires are **difficult** (near impossible?) to extinguish, and emergency response should consist in **isolation of the supply** and allowing the fire to burn itself while protecting the surrounding equipment with large amount of water.
- Fires in hydrogen vent systems and masts are also possible.

Quick Test

Quick questions

Fill out the blanks - Take the floor, raise your hand or add a comment

1. With a boiling point of …….. °C, Hydrogen liquid state can only be achieved through ……….. ………… .

2. ………. hydrogen refers to a production process where the CO2 produced is captured and sequestrated.

3. Hydrogen is highly …………….. and has a tendency to ………..

4. Local C02 emissions for a ship using an internal combustion engine running on 100% hydrogen fuel would be ……………

Quick questions

Fill out the blanks - Take the floor, raise your hand or add a comment

1. With a boiling point of **-253 °C**, Hydrogen liquid state can only be achieved through **cryogenic cooling**.

2. **Blue** hydrogen refers to a production process where CO2 produced is captured and sequestrated.

3. Hydrogen is highly **flammable** and has a tendency to **leak**.

4. Local C02 emissions for a ship using an internal combustion engine running on 100% hydrogen fuel would be **zero**.

Hydrogen
Situation today

Hydrogen Projects

Hydroville (2017) – the Origin

- **First LR Classed** vessel to use Hydrogen, Compagnie Maritime Belge (CMB), Antwerp
  - Lightweight catamaran construction
  - 2 x Hydrogen injected diesel engines, total shaft power 441kW
  - 12 Hydrogen tanks (205 litre @ 200 bar) & 2 diesel tanks
  - Max Speed 27 kn
- Operates in Port of Antwerp / River Scheldt for transportation during rush hour, occasionally longer trips and as a water taxi, 16 passengers & 2 crew
- **Demonstration platform** for Hydrogen propulsion.

LR Hydrogen Projects

Hydrotug 1, world’s first hydrogen tugboat

- Port of Antwerp-Bruges ordered the tug in 2019 from Compagnie Maritime Belge (CMB)
- Built at Armón Shipyards in Spain
- Dual fuel combustion engine
- Stores 415 kg of compressed hydrogen in 6 stillages installed on deck

Hydrotug 1, Image credit: Port of Antwerp-Bruges

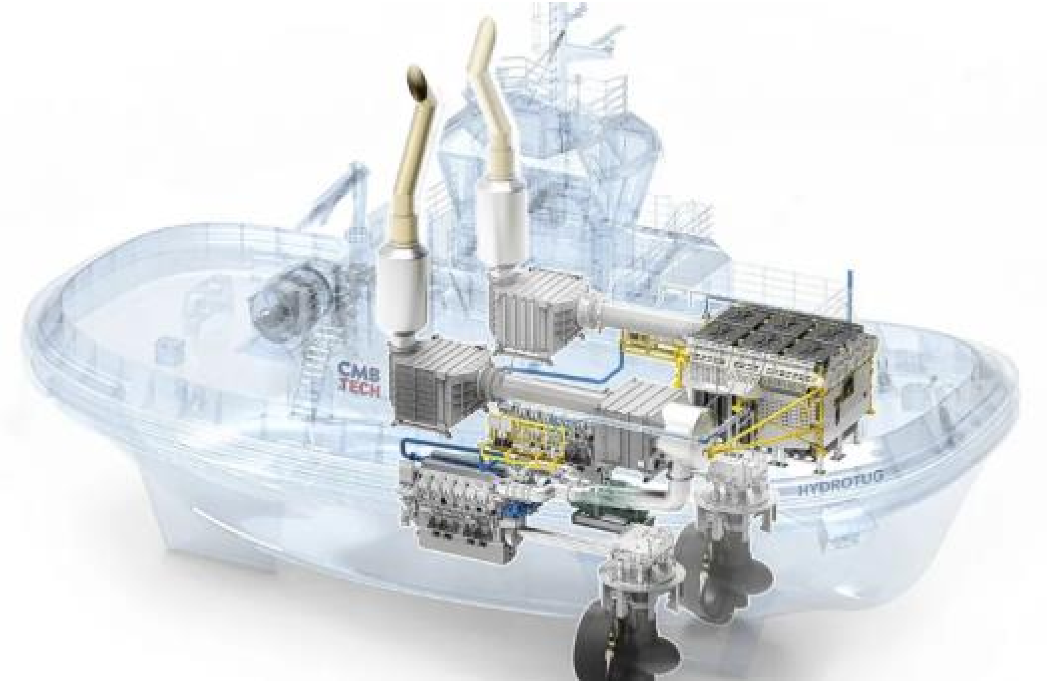
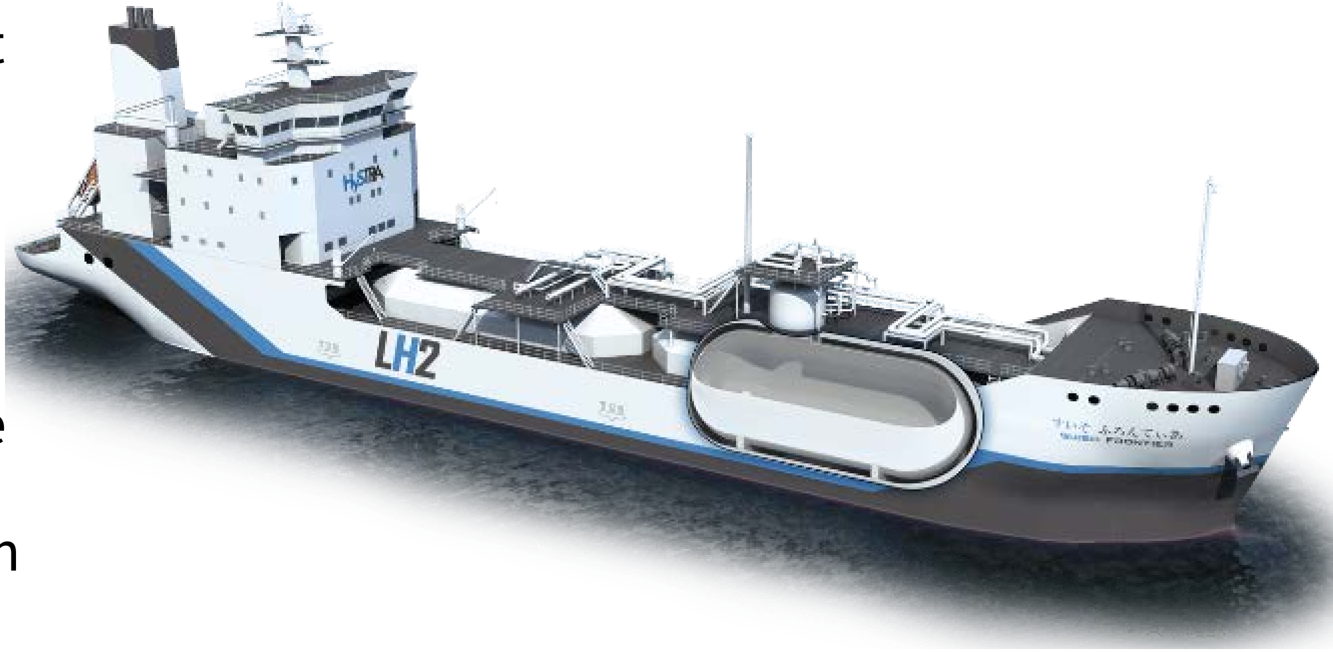


Image credit: CMB.TECH

Liquefied Hydrogen Carrier

Suiso Frontier - World’s first liquefied hydrogen carrier

The Suiso Frontier (LOA 116 m; 8 000 GT) built by Kawasaki Heavy Industries (KHI) in 2020 to transport liquefied hydrogen from the Port of Hastings, Victoria, to Kobe, Japan (2 weeks).



To keep LH2 at its cryogenic temperature, the **1 250 m3 tank** uses technologies developed for the Japanese Space center, with ultra-high thermal insulation:

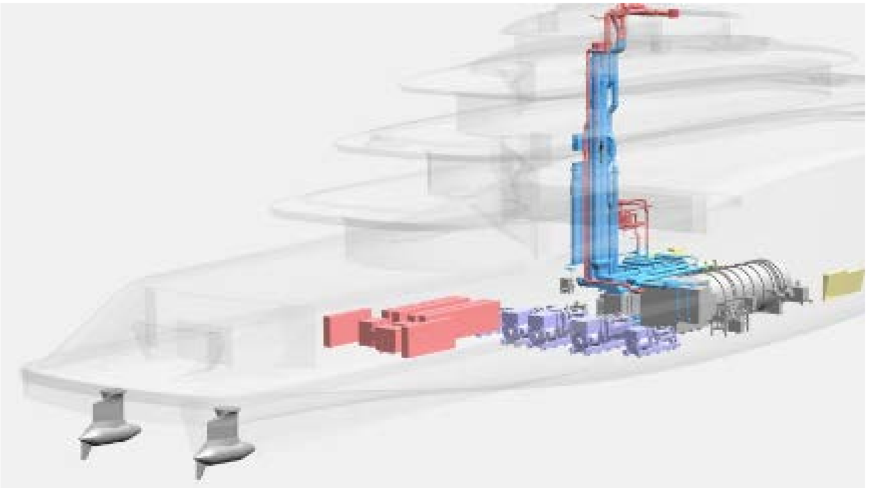
- double-shell structure with vacuum insulation between overlapping inner
- outer shell layers supported by high strength glass-fibre-reinforced plastic.

Credit: HESC Project website

LR Hydrogen Projects

Great prospects for the Large Yacht industry

- **Viareggio Super Yachts "Waterecho"**
  - Liquid Organic Hydrogen Carrier LOHC)
  - Application of Hydrogen **Fuel Cell technology** on a 65m Superyacht



- **Dutch shipyard Feadship**
  - cryogenic fuel tank, for liquified hydrogen around -250°C;
  - fuel cell bank

- **Yamaha Hydrogen Engine**
  - 5.0-liter V8 engine with 100% hydrogen power
  - Modifications to standard gas-powered engine included changes to the injectors, cylinder heads, and intake manifold

LR Hydrogen Projects

Approval In Principle

- (AiP) to Norwegian ship owner Torghatten Nord for **two hydrogen-powered vessel**s operating on Norway's longest ferry route
- Designed by Norwegian Ship Design, will use a minimum of **85% 'green hydrogen' based fuel**, to reduce CO2-emissions by **26,500** tons each year.
- The two main components of the hydrogen system on board are:
  - the hydrogen storage part, feeding hydrogen to fuel cells and
  - the fuel cells themselves, providing electric power for the propulsion and all other consumers on board.
- LR awarded the AiP following the completion of a comprehensive and constructive risk-based HAZID certification.

The two hydrogen-powered vessels will operate on Norway's longest ferry route.
Scheduled to enter operation in October 2025.
(Picture: Nowegian Ship Design)

LR Hydrogen Projects

Approval In Principle – Bulk Carrier

- (AiP) to Norwegian ship owner Egil Ulvan Rederi AS for its zero-emission self-discharging **hydrogen-fuelled bulk carrier,** With Orca
- With Orca will be fully zero-emission in **all operations**.
- It will be powered by hydrogen, stored onboard in **compressed form**, and the hydrogen combustion engine will be optimised for increased efficiency.
- The vessel will also have a **fuel cell system** for energy production in low load conditions.
- A significant part of the energy required to operate the 88 m/5,500 tonne vessel will be harvested directly from the **wind** through two large **rotor sails**.
- The vessel also has the ability to store excess energy in **batteries**.

Sailing route will mostly be in open waters in the North Sea, where weather conditions are ideal for wind-assisted propulsion. Scheduled to enter operation in early 2024.

Hydrogen Projects – HyDIME and HySEASIII (Scotland)

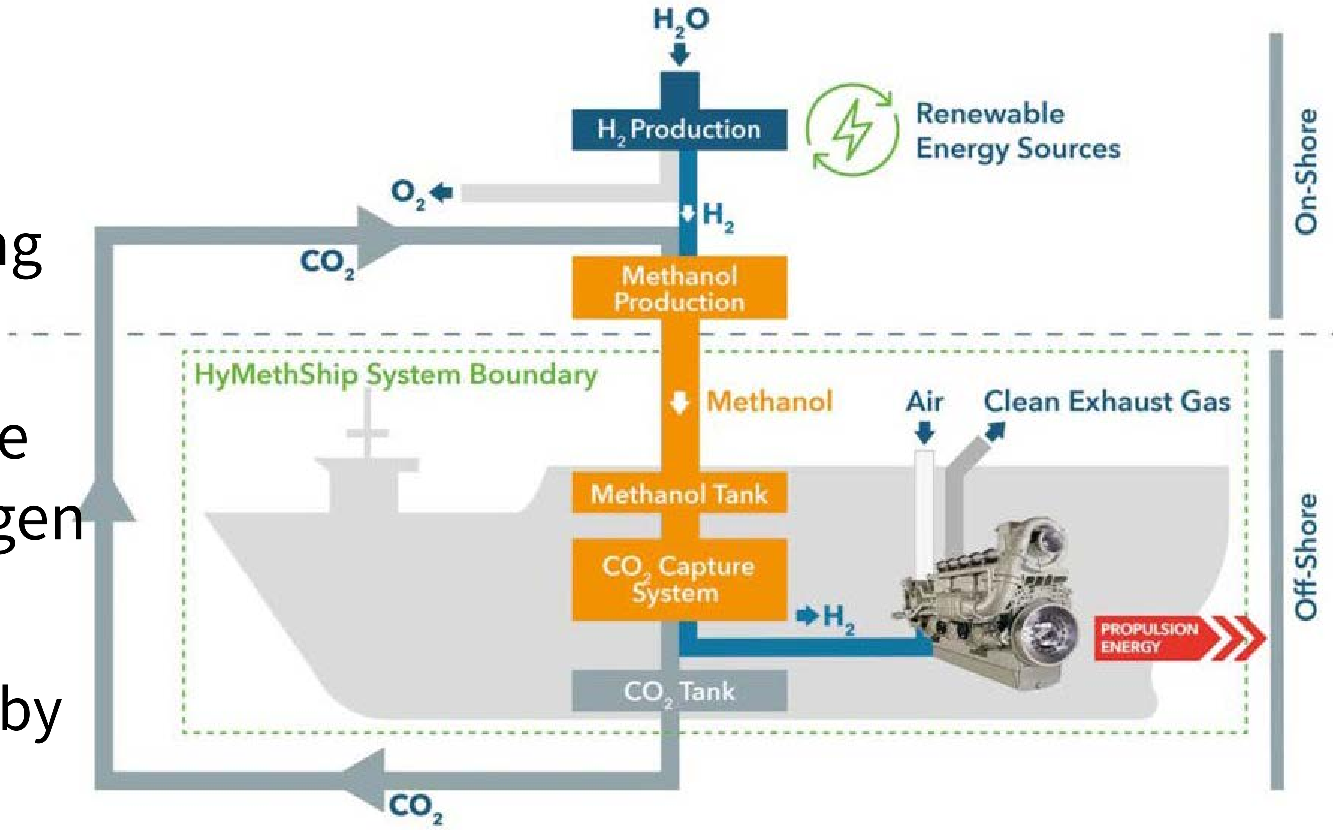
Hydrogen and **D**iesel **I**njection in a **M**arine **E**nvironment

- HyDIME project
- Integrate and trial an **innovative hydrogen/diesel dual fuel conversion system** for a 50kW **auxiliary** diesel unit
- Fit to an existing **small car ferry** in Orkney islands
- Pilot project to demonstrate and use of hydrogen fuel produced by **renewable** sources.
- **HySEASIII** – Hydrogen Fuelled Ferry powered by hydrogen fuel from renewable sources ("Green Hydrogen"). Initial stages of design and HAZOP commenced.

LR Hydrogen Projects

HyMethShip

- Hydrogen and Methanol Ship
- EU Research Project concept combining
  - membrane reactor, CO2 separation system, CO2 capture and storage system and hydrogen combustion system.
- Hydrogen as fuel **generated** on board by **reforming** methanol.



Hydrogen Powered Ships

Hydrogen Powered Ships

Curtesy of CMB.TECH – LR Class

Green Technology Uptake Dashboard

Alternative fuels: In-Service and Orderbook, Capable or Ready

Last refresh date: 17 Mar 2025

Show filters | Home

Filters applied

Alt. fuel status: Capable or Ready
Ship type group: Merchant & Leisure Vessels

Alternative fuels (excl. batteries/prop.)	Total No. vessels	LR share (No. vessels)	Total mGT	LR share (mGT)
	5,446	17.3%	361.9	20.6%

Display results by: Total fleet | Class | Ship type | Size band

Display results in: # vessels | % # vessels | mGT | % mGT

Maritime fuel breakdown

In-Service and Orderbook, Capable or Ready

Non-traditional fuel breakdown by capability

In-Service and Orderbook, Capable or Ready

Green Technology Uptake Dashboard

Alternative fuels: In-Service and Orderbook, Capable or Ready

Last refresh date: 18 Mar 2025

Show filters | Home

Filters applied

Alt. fuel status: Capable or Ready
Ship type group: Merchant & Leisure Vessels
Alt. fuel type Hydrogen

Alternative fuels (excl. batteries/prop.)	Total No. vessels	LR share (No. vessels)	Total mGT	LR share (mGT)
	136	22.1%	0.5	1.0%

Display results by: Total fleet | Class | Ship type | Size band

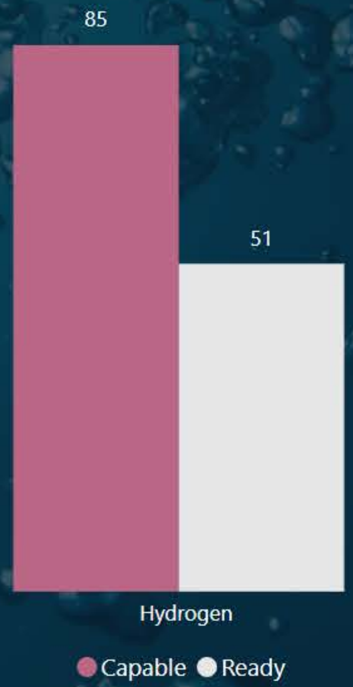
Display results in: # vessels | % # vessels | mGT | % mGT

Maritime fuel breakdown

In-Service and Orderbook, Capable or Ready

Non-traditional fuel breakdown by capability

In-Service and Orderbook, Capable or Ready



Green Technology Uptake Dashboard

Alternative fuels: In-Service and Orderbook, Capable or Ready

Last refresh date: 18 Mar 2025

Show filters | Home

Filters applied

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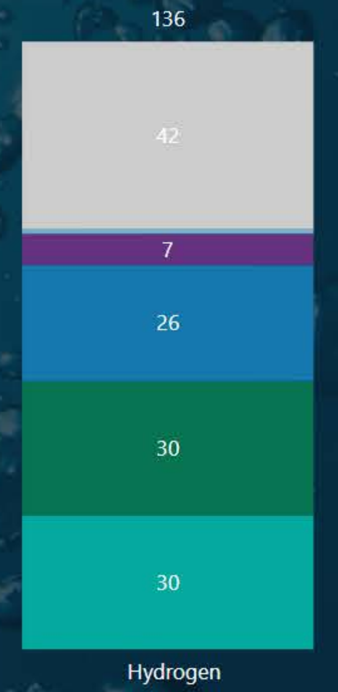
Maritime fuel breakdown by class society

In-Service and Orderbook, Capable or Ready

Non-traditional fuel breakdown by class society

In-Service and Orderbook, Capable or Ready



Thank you

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