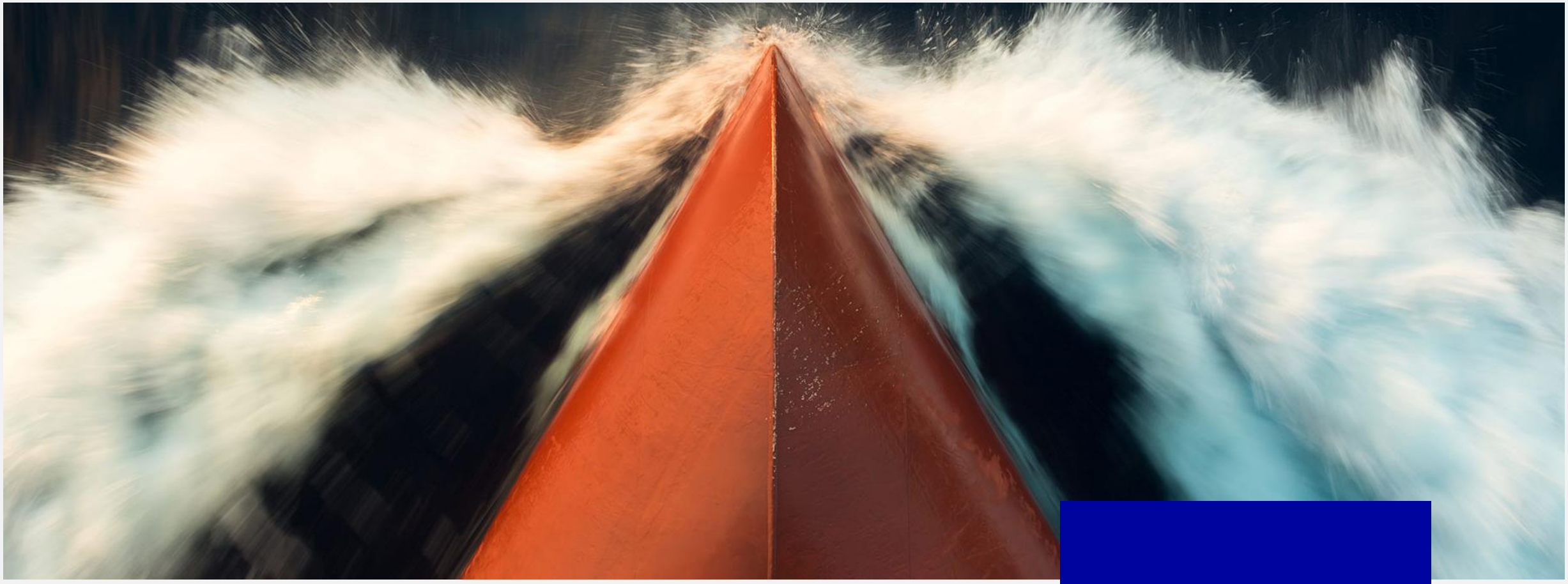


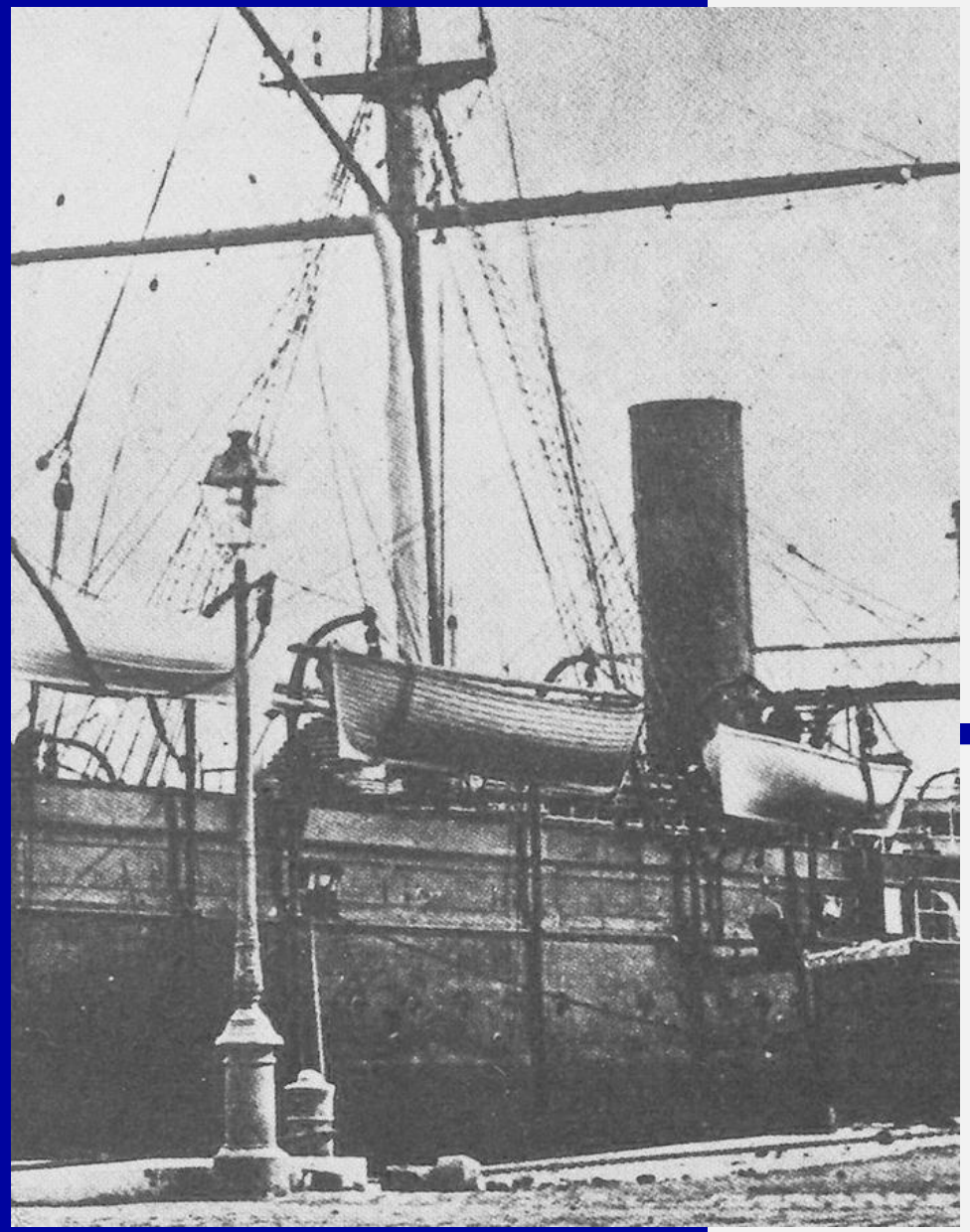
Liquified Hydrogen Presentation

LH2KC – The Hague
4 September 2025

Pim Reuderink MBA CSci IENg

BUREAU VERITAS

CONTENTS



Introduction

Bureau Veritas

Shaping the world of trust started in the Netherlands in 1828

KEY FIGURES

€6.2
billion

FY 2024

84 250
employees

400,000+
clients

~1 500
offices & laboratories

IN 140 COUNTRIES

Pim Reuderink MBA CSci IEng

Regional Technical Manager – Nordics & Netherlands

- **Chairman foundation CAB** – the Dutch pressure equipment scheme owner

- **Academic Researcher** (offshore) hydrogen and Chartered scientist:
  - HyTROS - Hydrogen Transport, Offshore and Storage
  - North Sea Energy - public-private research programme

- **Co-author pipeline standards** on hydrogen transport at Royal Dutch NEN (NEN 3650 /NEN 3656)

WAB e.V. Bremerhaven quote: *Proven expert, thought leader and public speaker on hydrogen.*

Leadvent Group Prague quote: *big thanks for your contribution as the Chairman and for your input in 9th Edition Green Hydrogen Forum in Amsterdam, 29-30 April 2025.*

BUREAU VERITAS AND HYDROGEN

Pioneering Hydrogen Safety and Certification

Strategic Focus: Supporting the hydrogen economy transition

Key Areas of Expertise:

- Safety assessment
- Certification services
- Technical inspection
- Risk management for hydrogen projects

Since 1921 in the Netherlands active on Hydrogen (Krachtwerktuigen and knalgas generators)

LH2 VESSEL CLASSIFICATION AND SAFETY

Project Highlights:

Developing safety standards for hydrogen-powered ships

Certification protocols for LH2 marine transportation

Risk assessment for hydrogen bunkering infrastructure

Key Contributions:

Comprehensive maritime hydrogen safety guidelines

Technical verification of hydrogen propulsion systems

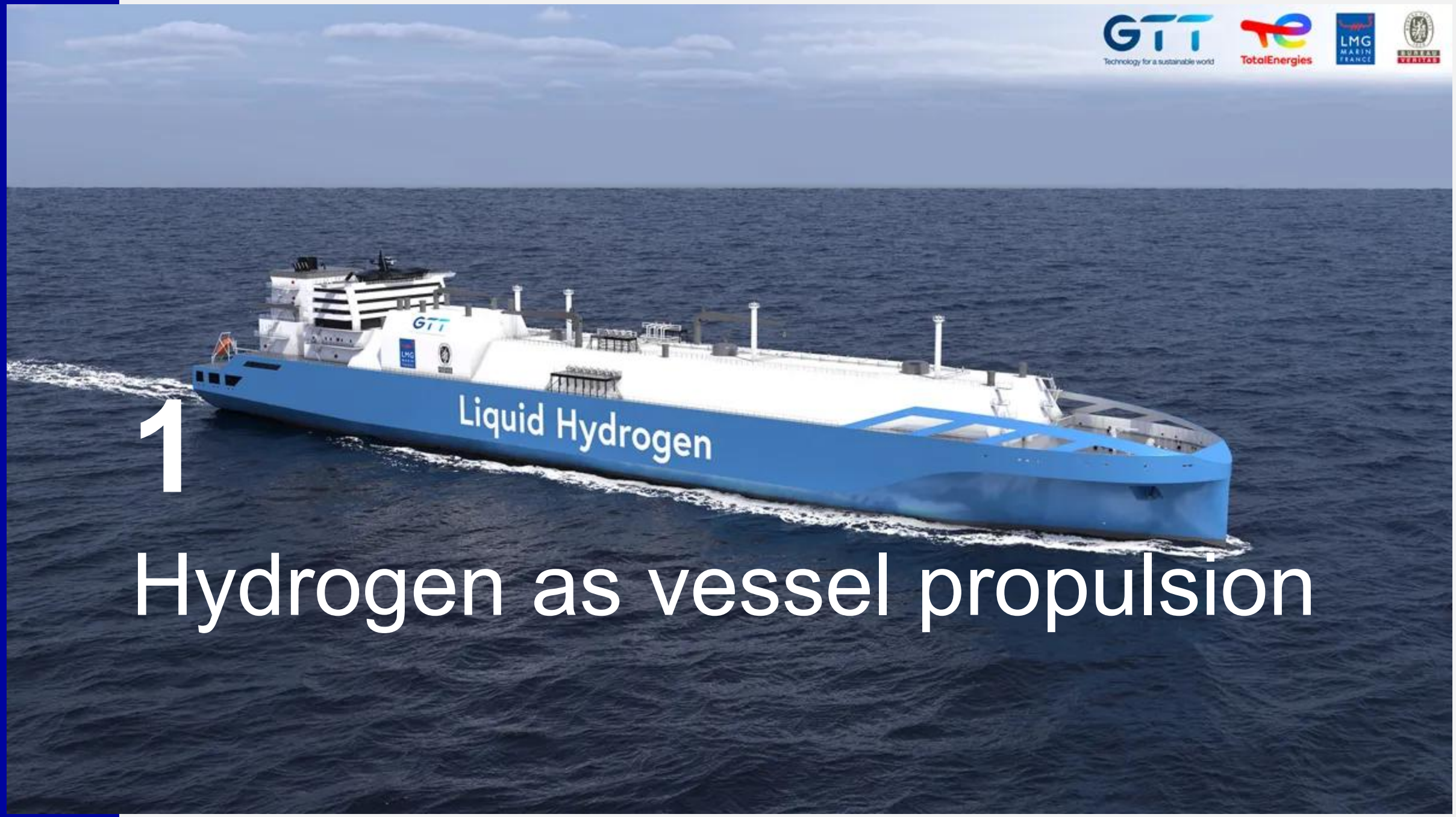
INDUSTRIAL LIQUIFIED HYDROGEN INFRASTRUCTURE

Project Scope:

- LH2 storage facility safety assessments
- Hydrogen production plant inspections
- Equipment certification for hydrogen systems

Technical Expertise:

- Cryogenic system evaluations
- Integrity management
- Compliance with international standards



1 Hydrogen as vessel propulsion

HYDROGEN : SOME FIGURES

Energy density : interesting in mass, not so much in volume

1 kg Hydrogen represents:

11 m3 @ ambient temperature & pressure

25 litres @ 700 bar

15 litres @ -253°C

16 kWh produced by a Fuel Cell (PEM)

Exemple for a car

1 litre of gasoline = 7 litres Hydrogen @700 bar

1 litre of gasoline = 4 litres Hydrogen @-253°C

1 kg H2 / 100km versus 7 litres gasoline / 100km

Property	Hydrogen	Comparison
Density (gaseous)	0.089 kg/m^3 (0°C, 1 bar)	1/10 of natural gas
Density (liquid)	70.79 kg/m^3 (-253°C, 1 bar)	1/6 of natural gas
Boiling point	-252.76°C (1 bar)	90°C below LNG
Energy per unit of mass (LHV)	120.1 MJ/kg	3x that of gasoline
Energy density (ambient cond., LHV)	0.01 MJ/L	1/3 of natural gas
Specific energy (liquefied, LHV)	8.5 MJ/L	1/3 of LNG
Flame velocity	346 cm/s	8x methane
Ignition range	4–77% in air by volume	6x wider than methane
Autoignition temperature	585°C	220°C for gasoline
Ignition energy	0.02 MJ	1/10 of methane

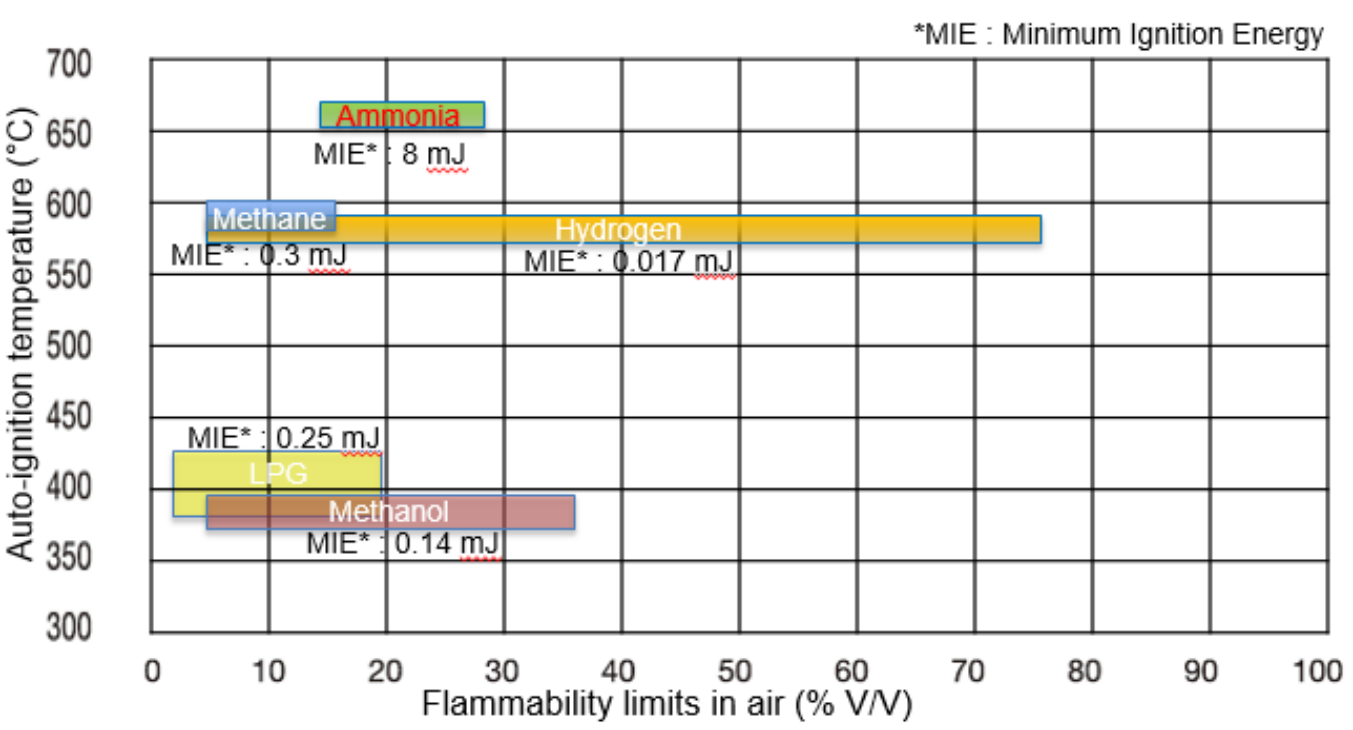
Notes: cm/s = centimetre per second; kg/m^3 = kilograms per cubic metre; LHV = lower heating value; MJ = megajoule; MJ/kg = megajoules per kilogram; MJ/L = megajoules per litre.

The Future of Hydrogen, IEA, 2019

HYDROGEN : SAFETY

A safety challenge

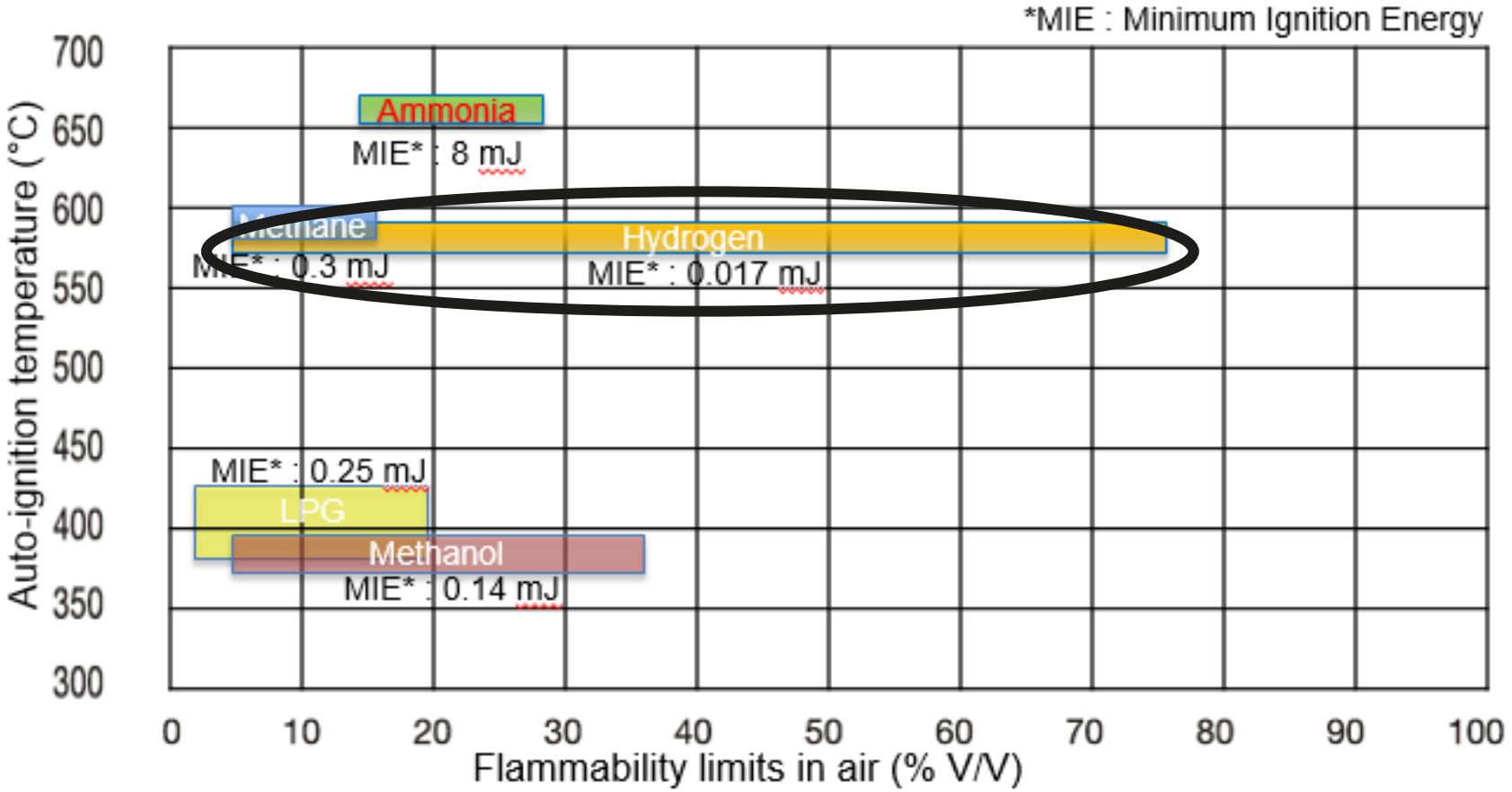
- Small molecule with very lw viscosity (challenging prevention of leaks)
- Wide flammability range
- Low ignition energy (small sparks may ignite)
- Rapid burning rate and invisible flame (2,045°C)
- Explosive range (from 8%, 11% for detonation)



HYDROGEN SAFETY

Hydrogen safety

- Wide flammability range
- Low ignition energy (small sparks may ignite)
- Small molecule with very low viscosity
- Low density (0.07)
- Rapid burning rate and invisible flame (2,045°C)

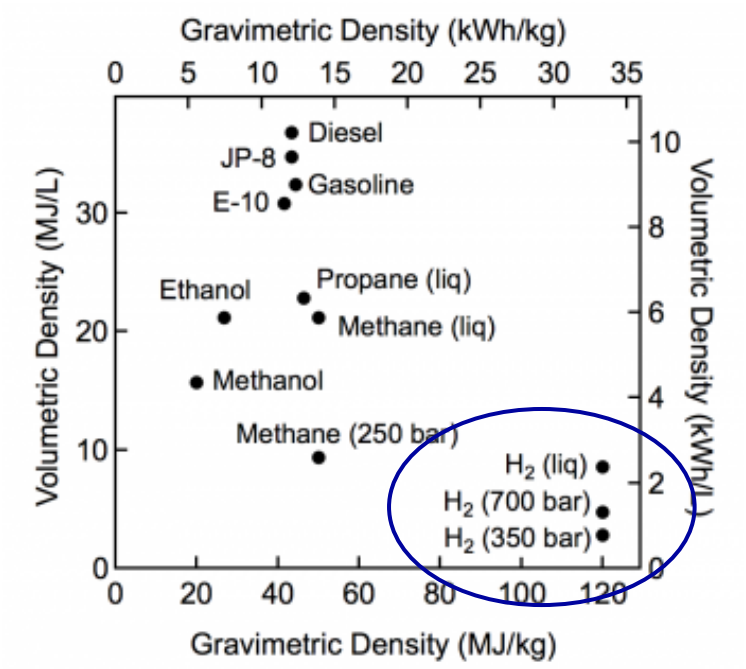


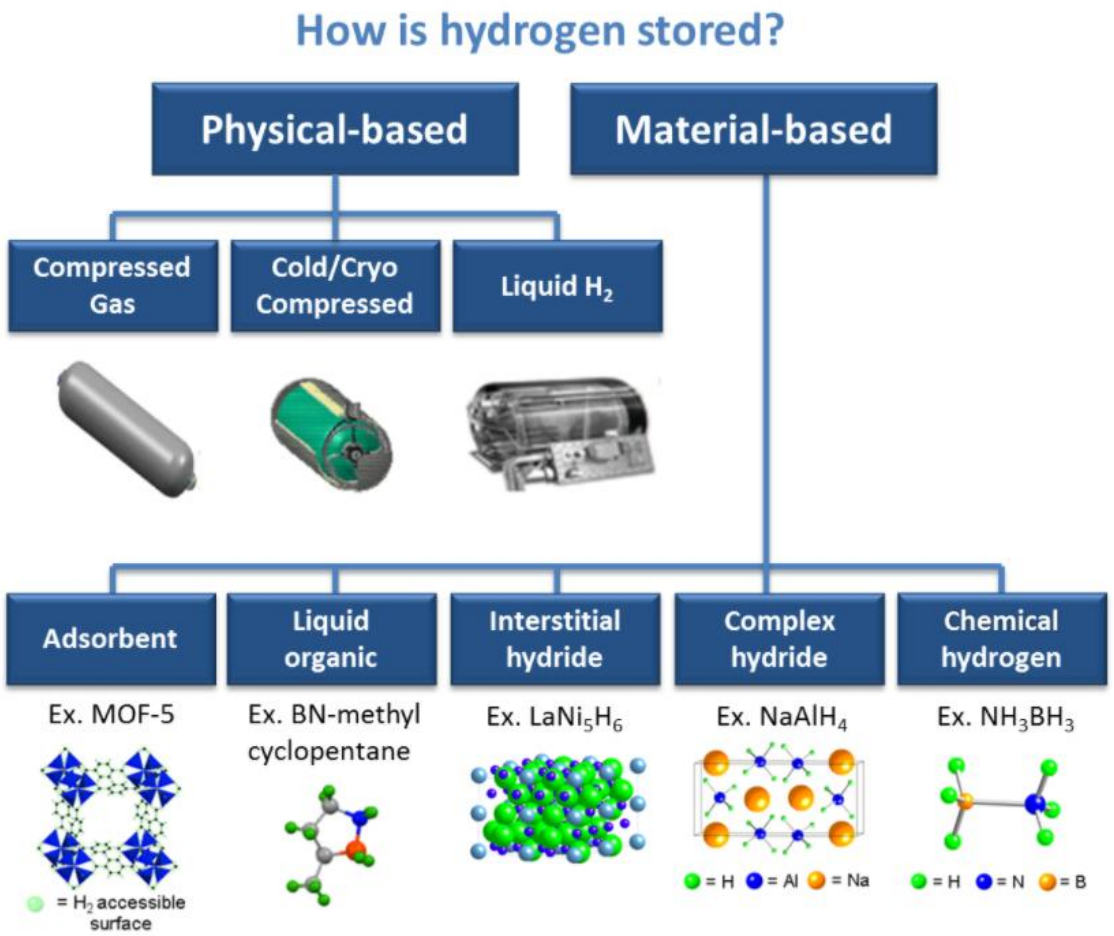
HYDROGEN STORAGE

Storage

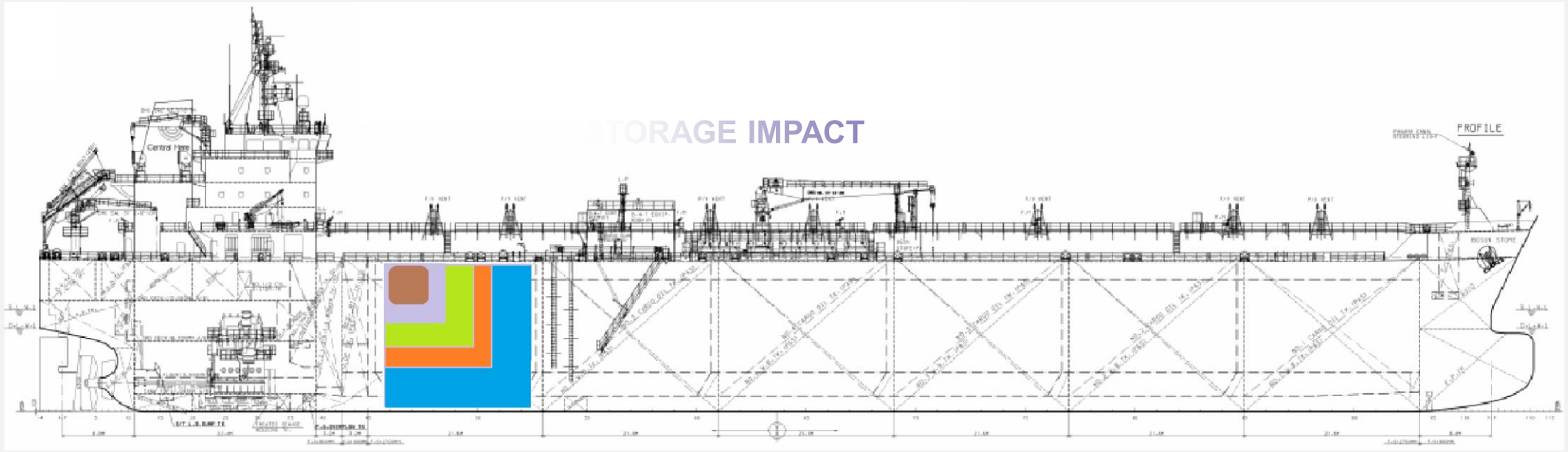
Compressed H2 (≤ 700 bars) or Liquid H2 (-253°C) are ready

Energy density is an issue



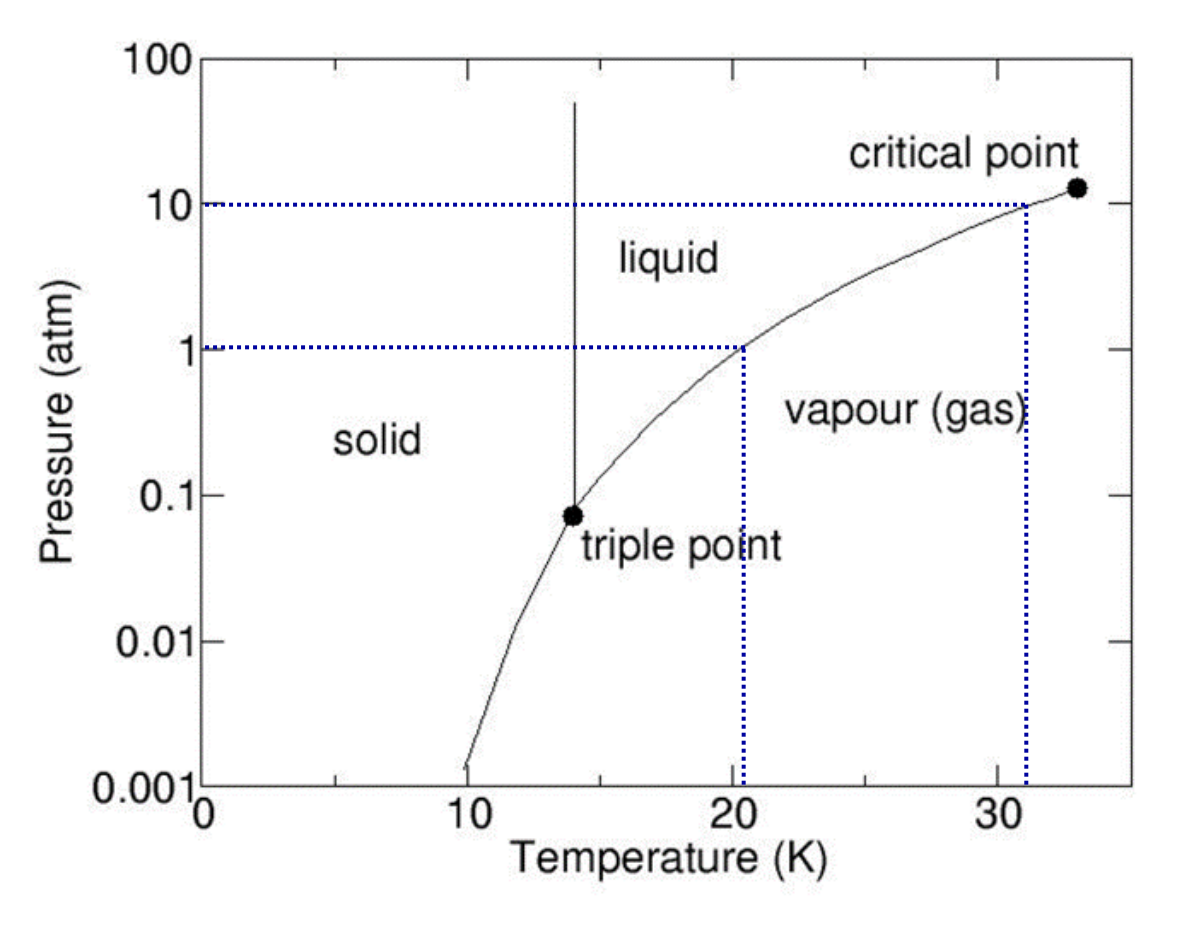


STORAGE OF HYDROGEN ONBOARD



MGO
LNG
MeOH
NH3
LH2

HYDROGEN TRANSPORT



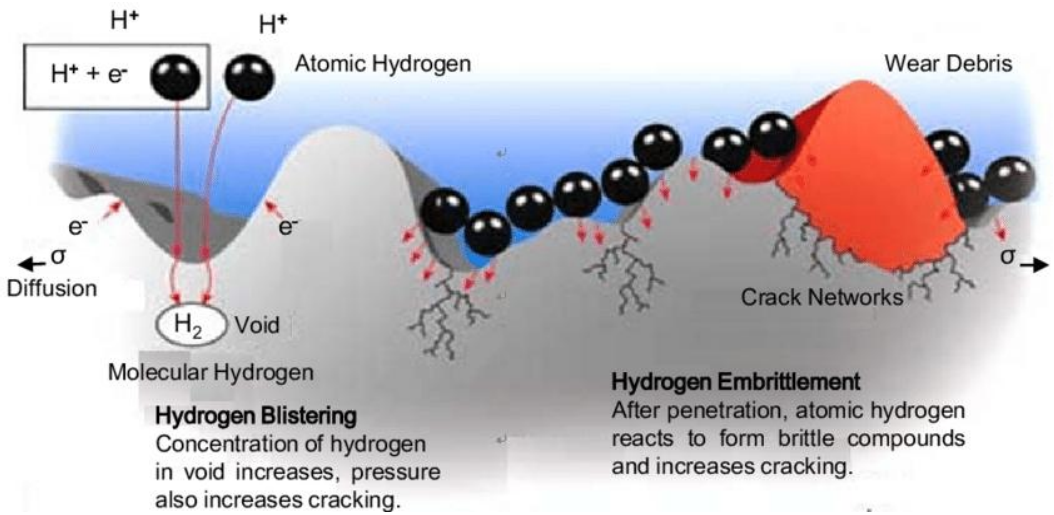
Conditions for transport : Pressure / Temperature diagram

10 degrees increase -> 10 atm increase

HYDROGEN EMBRITTLEMENT

Small hydrogen molecules can easily diffuse in materials

- Metallic materials and equipment may suffer from hydrogen embrittlement.
- Hydrogen embrittlement is the penetration of hydrogen causing loss of ductility and tensile strength.
- It may lead to micro-cracks, brittle fractures and eventually leakages.
- Selection of materials : composition, tensile strength, grain size and micro-structure and appropriate thickness.
- Special surface treatment and coatings can be used to protect against hydrogen absorption.
- Stainless steels, aluminium and copper are generally less susceptible to hydrogen embrittlement.



LH2 CORE MATERIAL

Material Suitability

Austenitic stainless steels like 1.4435, and 1.4571 are preferred due to their ductility and toughness at -253°C.

Performance Insights

1.4435 (high Ni content ~13%): Shows no ductility loss after hydrogen exposure—ideal for pressure-bearing parts 1.

1.4404 and 1.4571: Show severe ductility loss, even with high Ni-equivalent values. Titanium in 1.4571 may contribute to embrittlement.

Recommended Ni content: ≥12.5% for hydrogen service; Ni-equivalent ≥29.5 is a general guideline

Cost & Availability

1.4435 is more expensive due to higher nickel content and specialized production, but offers superior hydrogen compatibility.

Prices vary based on alloy composition, form (plate, pipe, tank), and supplier, but expect premium pricing for LH_2-grade materials due to strict quality and cryogenic performance requirements.

Avoid carbon steel

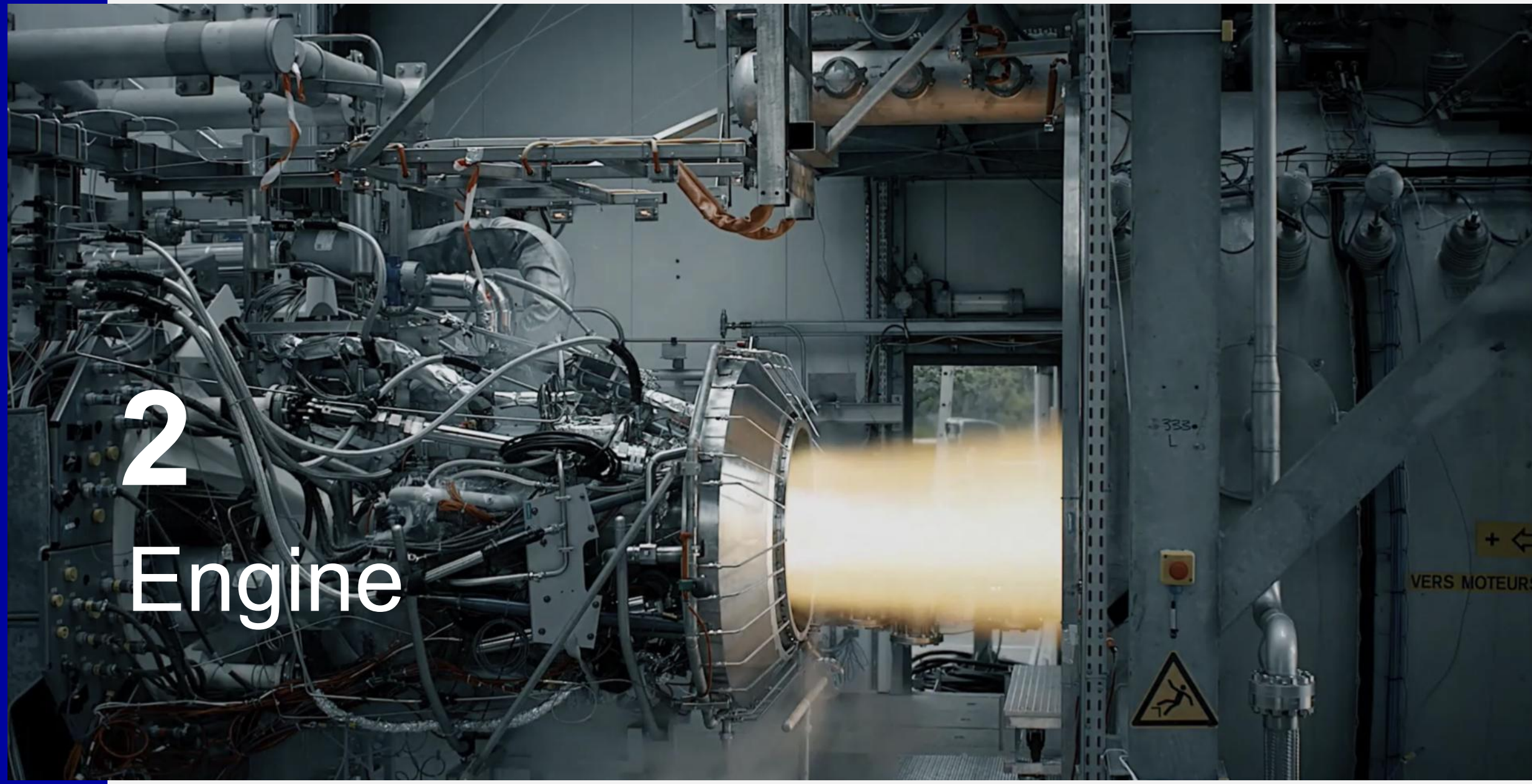
HYDROGEN AS MARINE FUEL - EMISSIONS

Hydrogen leakage may lead to indirect radiative forcing, as highlighted in a recent UK government study which estimated a GWP of 11 ± 5 over 100 years.
Highlights the absolute need to limit leakage, even for non-direct GHG like hydrogen

Name	Formula	20-year GWP	100-year GWP
Carbon dioxide	CO_2	1	1
Methane	CH_4	81.2	27.9
Nitrous oxide	N_2O	273	273
Hydrogen	H_2	33	11

Note: Global warming potential taken from IPCC AR6 and for hydrogen from Warwick et al "Atmospheric implications of increased Hydrogen Use", 2022 report for the UK Government

Graphical credit SGMF



2 Engine

HYDROGEN TECHNOLOGY : ENGINE AND FUEL CELL

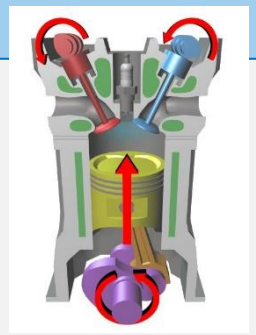
INTERNAL COMBUSTION ENGINE

DUAL FUEL ENGINES

- Claimed increased efficiency and emission reduction
- TRL 8

FULL HYDROGEN ENGINE

- Expected high level of emission reduction and increased engine efficiency
- TRL 4-5

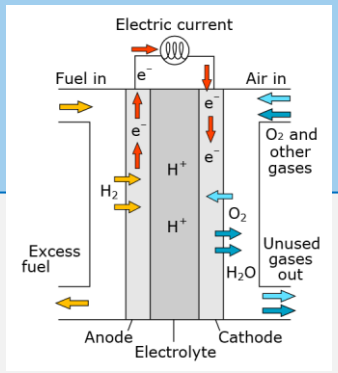


And also, Gas Turbine, to be investigated.....

Fuel cell

PEMFC and SOFC are most likely to be used onboard ships

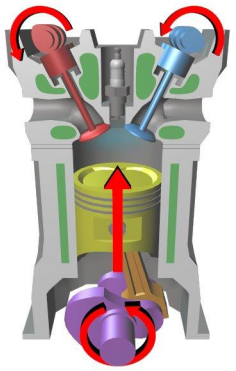
- PEMFC: up to 1 MW, flexible in transient
- SOFC: more power output and fuel flexibility but long start up & limited shut down



HYDROGEN TECHNOLOGY

Internal combustion engine

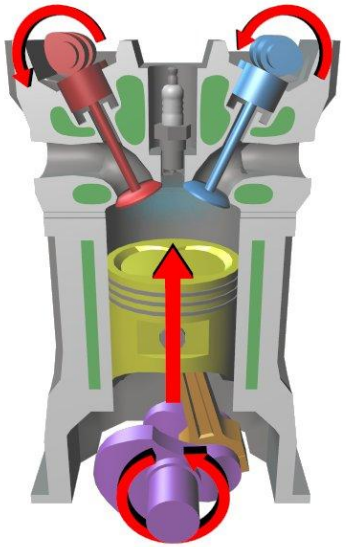
- Dual fuel engines
  - Claimed increased efficiency and emission reduction
  - TRL 8 for short-medium distance ships
- Full H2 engine
  - Expected high level of emission reduction and increased engine efficiency
  - TRL 4-5 for long distance ships



HYDROGEN INTERNAL COMBUSTION ENGINE

Dual fuel engines

- Diesel cycle with pilot fuel(up to 60% H2)
- Actual engines can be adapted
- Claimed increased efficiency (~10%)
- Claimed emission reduction (-65% Nox)
- TRL 8 for short-medium distance ships



Full Hydrogen engine

- Otto cycle (spark-ignition)
- Expected high level of emission reduction
- NOx management
- Expected increased engine efficiency
- Larger engine size due to lower power output and hardened materials
- Backfire risk to be prevented
- TRL 4-5 for long distance ships

3

LH2 Projects

LH_2 CARRIER VESSEL

Partners: Bureau Veritas, GTT, TotalEnergies, LMG Marin

Objective: Development of a **150,000 m³ liquid hydrogen (LH_2) carrier** for maritime transport.

Innovation Highlights:

- GTT designed a **membrane-type containment system** for LH_2 at -253°C.
- LMG Marin developed the vessel design.
- Bureau Veritas conducted **risk assessments** and granted **Approval in Principle** for safety and design.

NAVHYS – EUROPEAN RESEARCH PROJECT

Liquid Hydrogen (LH_2) Innovation for Maritime Applications

Project Overview

Full Name: NAVHYS – LH_2 Storage and Fuel-System Below Deck

Launch Date: January 2025

Duration: 36 months

EU Funding: €5 million (Clean Hydrogen Partnership)

Coordinator: ArianeGroup

Partners: Bureau Veritas, ENGIE, INERIS, RISE, VARD, Gas and Heat, University of Birmingham, and others

NAVHYS - GOAL

Objectives

- Develop a below-deck LH_2 storage and fuel distribution system for Service Operation Vessels (SOVs).
- Enable decarbonized offshore wind support vessels with up to 10 days of autonomous operation.
- Achieve Technology Readiness Level (TRL) 8–9 by 2030, targeting real-world deployment by 2035–2040.

Technical Highlights

- Tank Capacity: 200–300 m^3 (12–18 tonnes LH_2)
- Bunkering Rate: 10 tonH_2/hour
- Fuel System Output: GH_2 at 5 bar ambient, supporting 500 kW to 2 MW propulsion systems
- Design Innovations:
- LH_2 pump based on Ariane 6 space tech
- Robust against sloshing and boil-off
- Integration of cryogenic space expertise into maritime design.

LATTACE – FLOATING LH_2 IMPORT TERMINAL

Project Overview

Developer: LATTICE Technology Co., Ltd.

Approval: Bureau Veritas granted **Approval in Principle (AiP)** in September 2023**1**

.

Terminal Type: **75,000 m³ floating liquefied hydrogen (LH_2) import terminal**.

Platform: Barge-mounted, non-propelled floating unit.

4 Space application LH2

GUIANA SPACE CENTRE (CSG)

Kourou, French Guiana

Main launch site for **Ariane 5**, **Ariane 6**, and **Vega** rockets.

LH2 services

An **ATEX Ignition Assessment** is a safety evaluation conducted to ensure that equipment used in potentially explosive atmospheres complies with the ATEX directive. Here are three key bullet points describing it:

Hazard Identification: Evaluates whether equipment or components could act as an ignition source (e.g. sparks, hot surfaces, static discharge) in explosive atmospheres involving gases, vapors, or dust.

Risk Analysis & Mitigation: Assesses the likelihood and consequences of ignition events, and recommends design or operational changes to eliminate or control ignition risks.

Compliance Verification: Ensures that the equipment meets ATEX certification requirements, including proper classification for zones, temperature classes, and protection types.

BUREAU
VERITAS

Shaping a World of Trust