State of the Art of Hydrogen Storage and Utilization for Marine Applications

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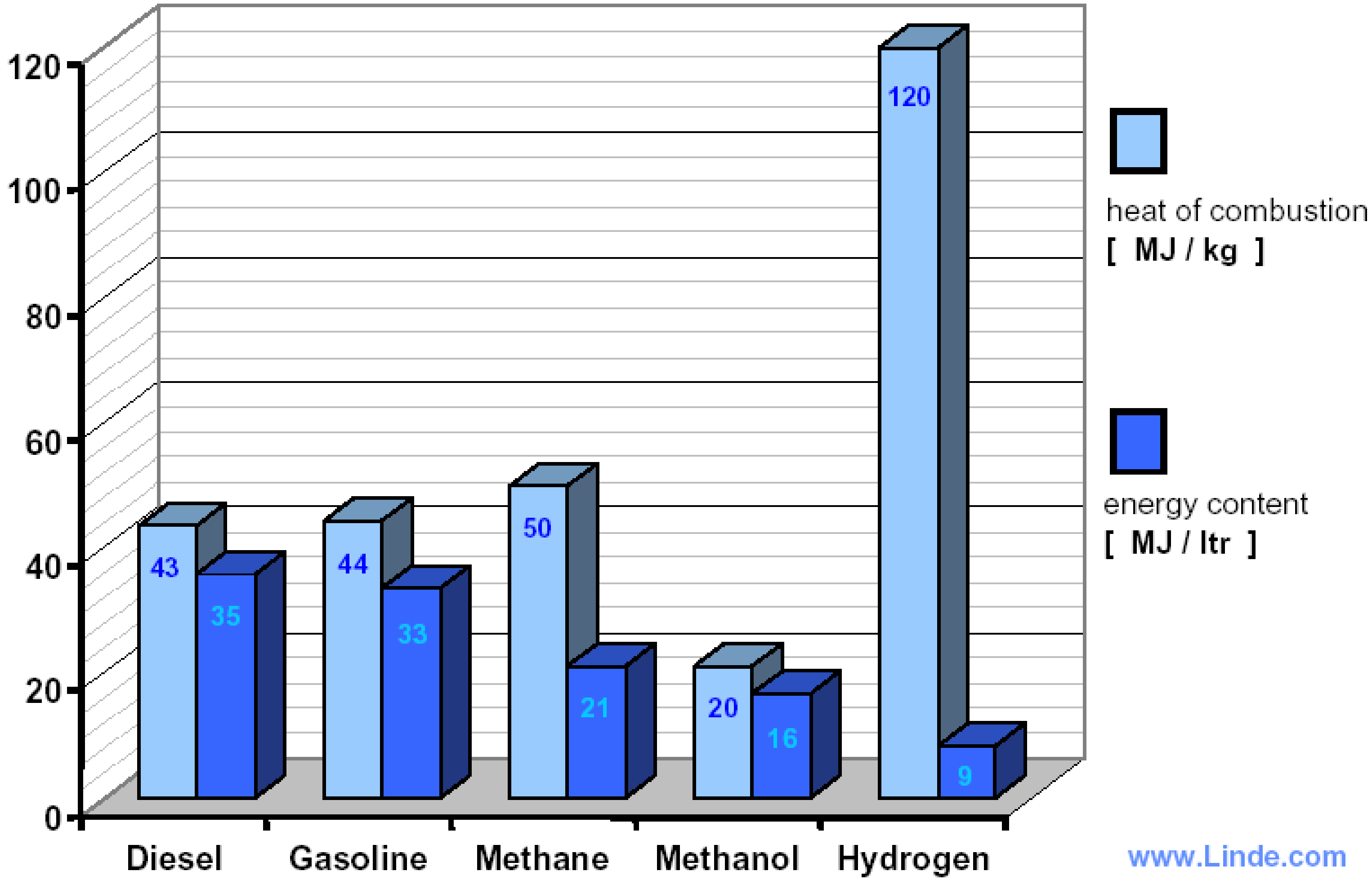
Hydrogen as Alternative Fuel

comparison of fuels - heat of combustion / energy content -



www.Linde.com

Linde Gas AG

wolf, sde, 1760, Fach 60

	NH_3 (-33°C)	LH_2 (-253°C)	MDO	LNG (-162°C)	LPG	MeOH	Biofuels (HVO)
Storage Density [kg/m³]	682	71	850	470	537	790	850 - 900
Lower Heating Value [MJ/kg]	18,8	120	44	48,6	45,5	19,8	37,8
Autoignition Temperature [°C]	630 - 650	580	225	537	410 - 580	470	204
Toxicity	Toxic	Not Toxic	Not Toxic	Not Toxic	Not Toxic	Toxic	Not Toxic
Net Volumetric Energy Density [MJ/m³]	12822	8540	35700	21840	24433	15641	34020
Gross Volumetric Energy Density [MJ/m³]	≈ 10500	≈ 6400	-	≈ 13000	≈ 18500	≈ 14000	-
Flammability Limit [%vol]	15 - 28	4 - 75	1,8 – 8,2	4 - 15	1,8 - 10	6,7 - 36	0,6 – 7,5
Converters (TRL ≥ 5)	- ICE - FC - GT	- ICE - FC - GT	- ICE - GT	- ICE - FC - GT	- ICE - GT	- ICE - FC	- ICE

Compared to current standard (MDO)		NH_3 (-33°C)	LH_2 (-253°C)	LNG (-162°C)	LPG	MeOH	Biofuels (HVO)
	Net	≈ 36%	≈ 24%	≈ 64%	≈ 68%	≈ 44%	≈ 95%
	Gross	≈ 28%	≈ 18%	≈ 36%	≈ 52%	≈ 39%	-

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Overview

Table 4. Storage methods overview.

Method	Gravimetric Energy Density (wt %)	Volumetric Energy Density (MJ/L)	Temperature (K)	Pressure (barg)	Remarks
Compressed	5.7	4.9	293	700	Current industry standard
Liquid	7.5	6.4	20	0	Boil-off constitues major disadvantage
Cold/cryo compressed	5.4	4.0	40–80	300	Boil-off constitues major disadvantage
MOF	4.5	7.2	78	20–100	Attractive densities only at very low temperatures.
Carbon nanostructures	2.0	5.0	298	100	Volumetric density based on powder density of 2.1 g/mL and 2.0 wt % storage capacity.
Metal hydrides	7.6	13.2	260–425	20	Requires thermal management system.
Metal borohydrides	14.9–18.5	9.8–17.6	130	105	Low temperature, high pressure thermal management required
Kubas-type	10.5	23.6	293	120	
LOHC	8.5	7	293	0	Highly endo/exothermal requires processing plant and catalyst. Not suitable for mobility
Chemical	15.5	11.5	298	10	Requires SOFC fuel cell.

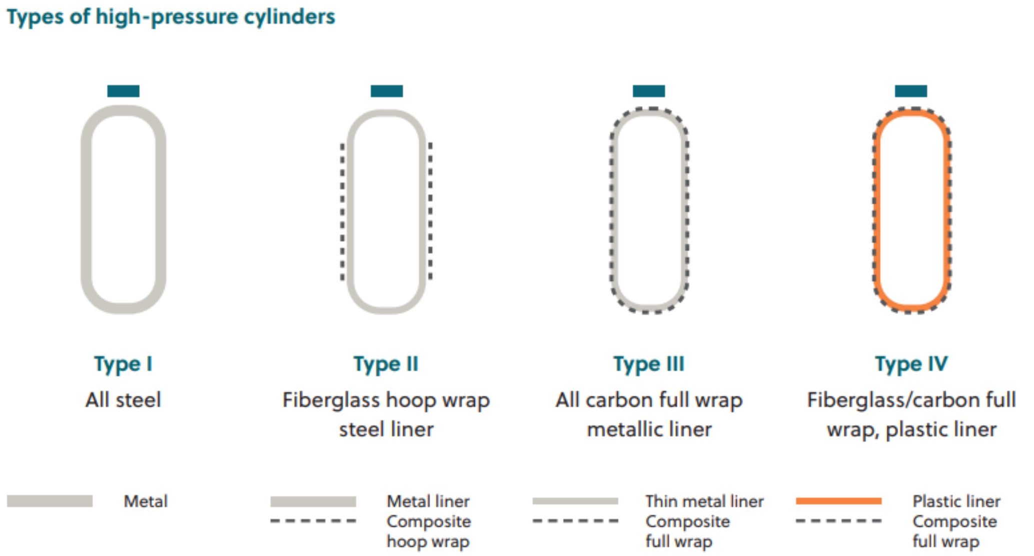
Rivard , Trudeau, Zaghib, «*Hydrogen storage for mobility: A review*», Materials, 2019

CGH_2 as marine fuel

- Zero-carbon emission fuel
- High mass-LHV compared to any other fuel
- H_2 may be exploited in different converters with high efficiencies

Drawbacks:

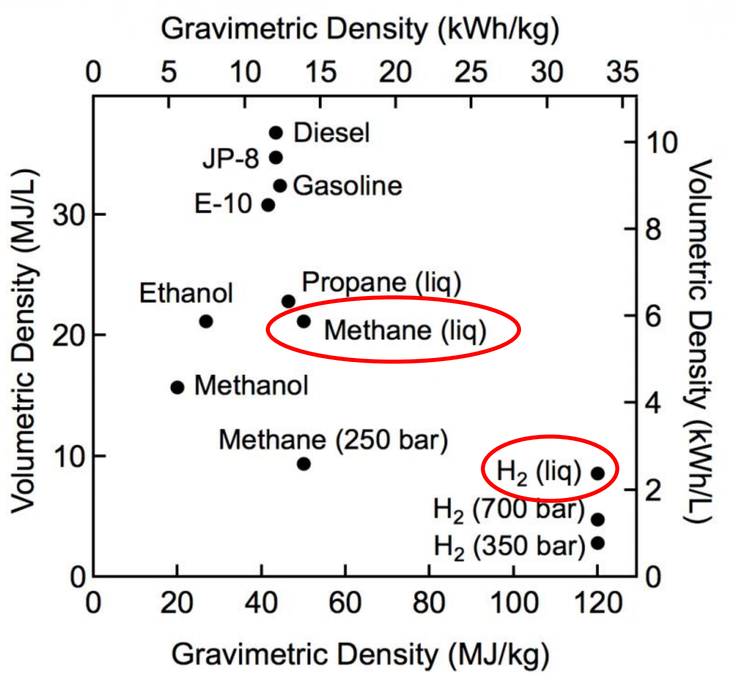
- Low storage energy density w.r.t. liquefied hydrogen
- Stricter safety concerns



Fuel	Stored density [kg/m³]	Energy density [MJ/m³]
MDO	830	35000
CGH_2 (350 bar)	23,7	2844
CGH_2 (700 bar)	39,7	4768
LH_2	71	8540
LNG	430	21400

LH_2 as marine fuel

Liquid storage guarantees the highest energy density for physical based H_2 storage



- Major challenges:
  - ➢ Efficient cryogenic storage
  - ➢ Regasification and feeding system to the prime mover
  - ➢ Stricter safety concerns

First Liquid Hydrogen tanker, KHI *Suiso Frontier*, operative

First Liquid Hydrogen powered ferry, *Norled Hydra* MF, operative

Towards LH_2 through LNG experience

Property	LH_2 VS LNG	Comment
Reactivity with materials	LNG	Higher reactivity. H_2 requires high quality materials
Heat capacity	LH_2	LH_2 has higher heat capacity, advantageous in liquid storage
Heat flux from surroundings	LNG	Consequence of lower temperatures (provided that insulation is equal)
Flammability range in air	LNG	Flammable conditions are more easily formed with hydrogen
Ignition energy	LNG	Hydrogen clouds are more easily ignited than NG clouds
Ignition temperature	LNG/0	Natural gas has slightly higher ignition temperature
Liquid phase ΔT in range 1-10 bar	LNG	13 °C vs. 30 °C. Requires more efficient control of heat leakage
Laminar flame speed in air	LNG	Higher for hydrogen, i.e., greater risk of spreading fire
Dense phase behaviour of leakages	LH_2/0	Similar behaviour. Both have density higher than air at near condensation temperature, but hydrogen tends to escape faster

Nerheim, Æsøy and Holmeset, "Hydrogen as maritime fuel – can experiences with LNG be transferred to hydrogen systems?", Journal of Maritime Science and Engineering, 2021

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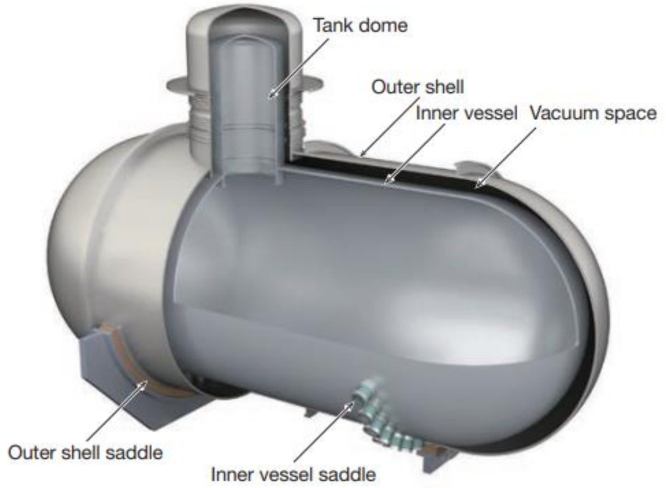
The Suiso Frontier and the HySTRA project

The *Suiso Frontier*, carries 1250 m^3 (~90 tons) LH_2 betwen Kobe (JAP) and Hastings (AUS) as part of the HySTRA International Project

The cryo vessel and the loading/unloading terminals are located in the airport island (8 km away from the commercial port)

In December,A delegation of TPG visited the storage site at Kobe port



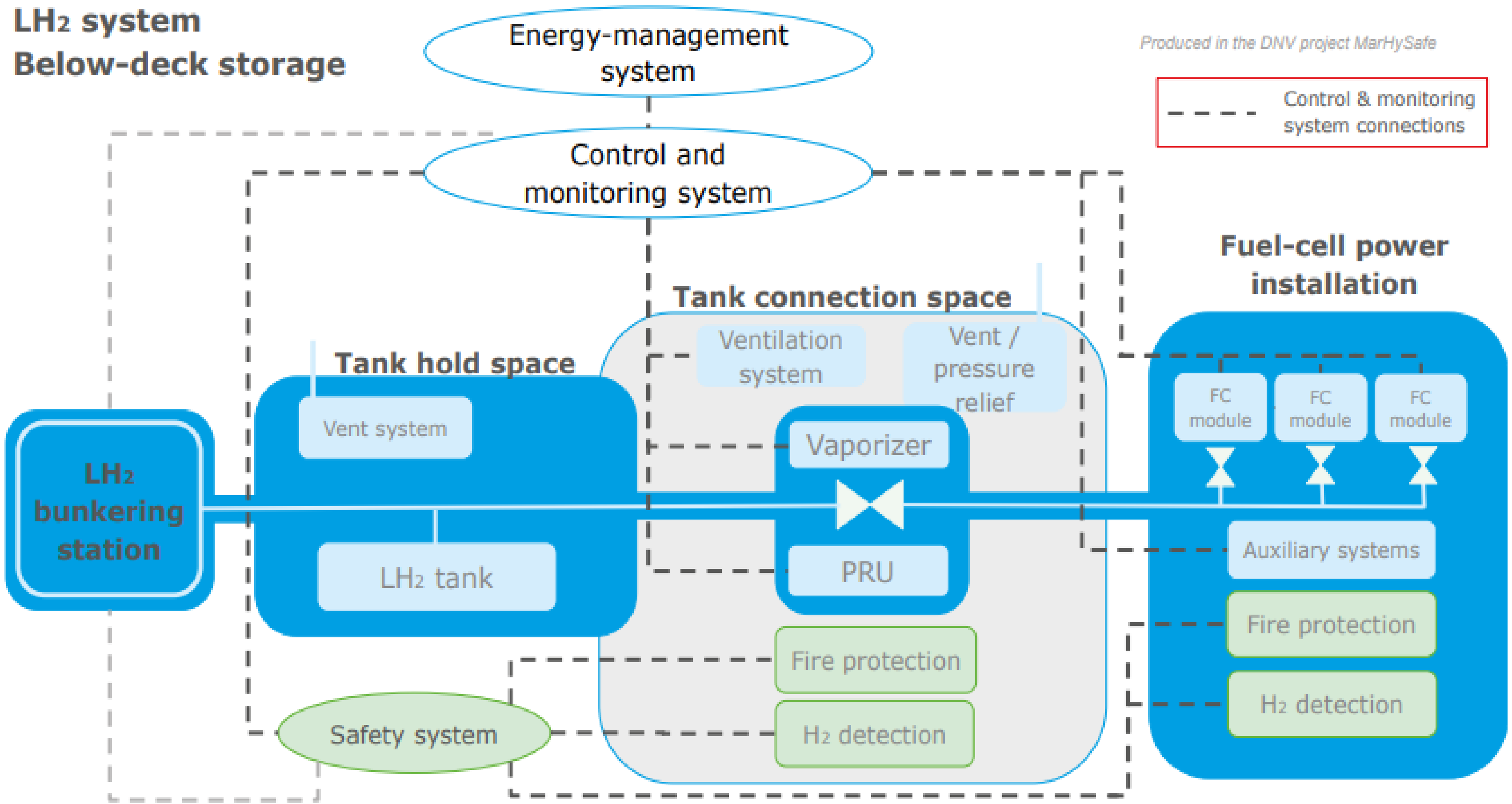
The Norled Hydra

The first (and up to the present only) LH_2 powered ship is a short-sea ferry in service among the norwegian southern fjords

Liquid hydrogen is stored in a cylindrical tank located on the open deck for safety reasons

The fuel is supplied via insulated truck trailer

Handling systems layout - 1



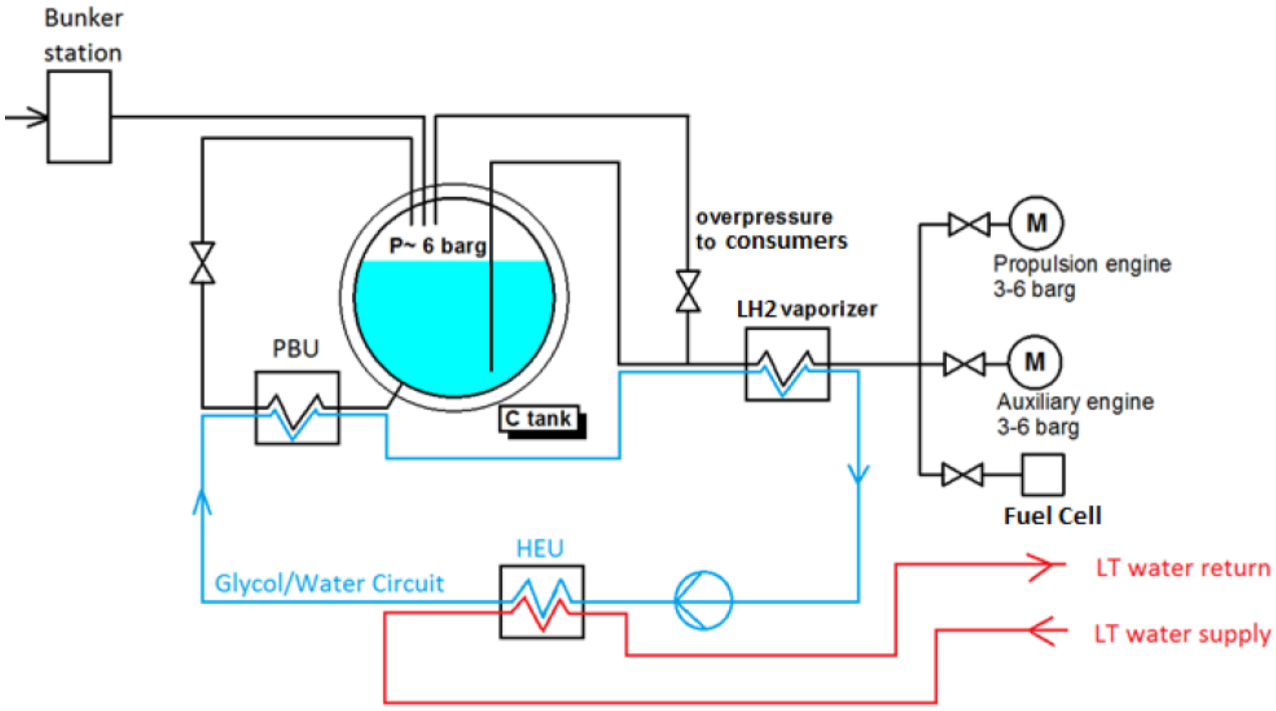
DNV, "*Handbook for Hydrogen-fuelled Vessels*", Deliverable, MarHySafe project, 2021

Current safety recommendations discourage below-deck storage of hydrogen

However, DNV has formulated a conceptual LH_2 sub-deck handling system layout in the scope of MarHySafe project

This should enhance LH_2 uptake as alternative fuel

Handling systems layout - 2



MAN Energy Solutions/MAN Cryo, "*LH_2 Marine Power Pack – Hydrogen Power Pack for Passenger Vessels*", 2021

Scarce insight is available on the topic due to the lack of market-ready solutions. A couple of them are reported hereby:

- MAN Energy Solutions has a marine-ready LH_2 engine feed system (figure)
- Linde has a product for automotive refueling stations (from LH_2 to high pressure hydrogen)
- Wartsila has developed an onboard LNG reforming system to produce hydrogen and separate CO_2

Besides, several research-scale solutions or prototypes exist

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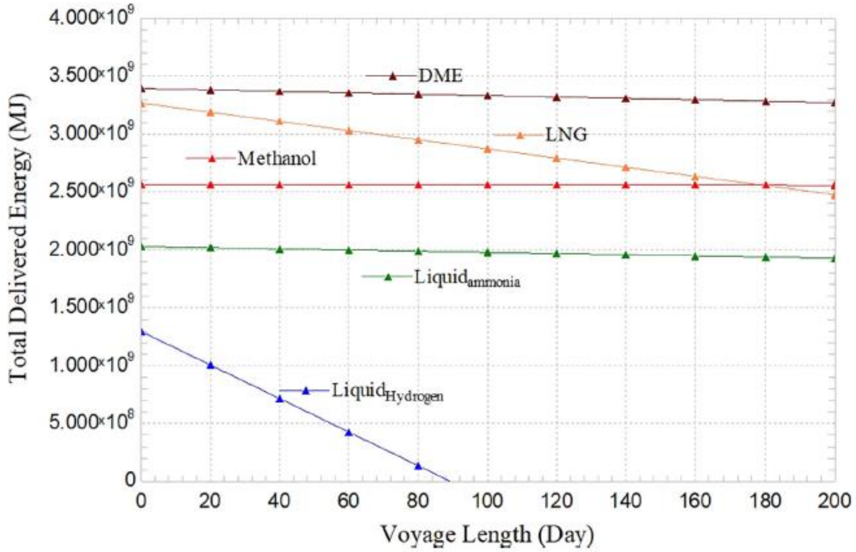
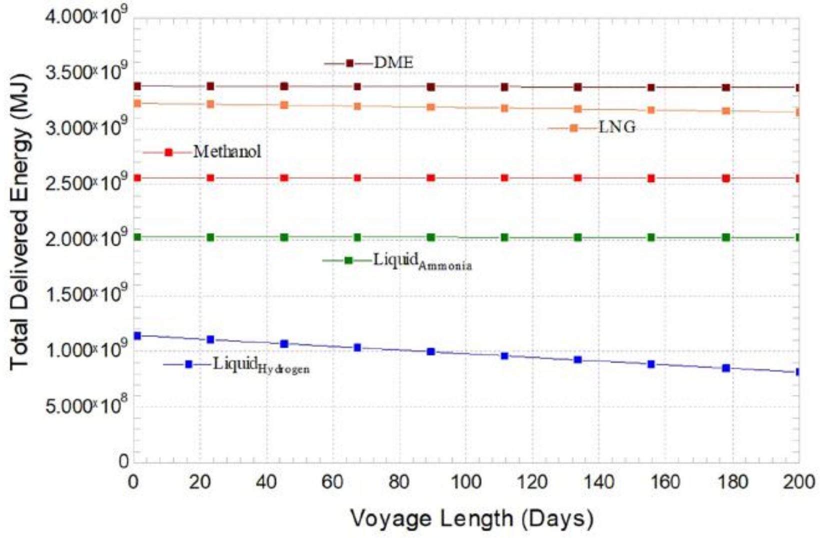
The problem of boil-off gas (BOG) - 1

The total energy decreases due to the boil off: hence the cruciality of handling the evaporated BOG.

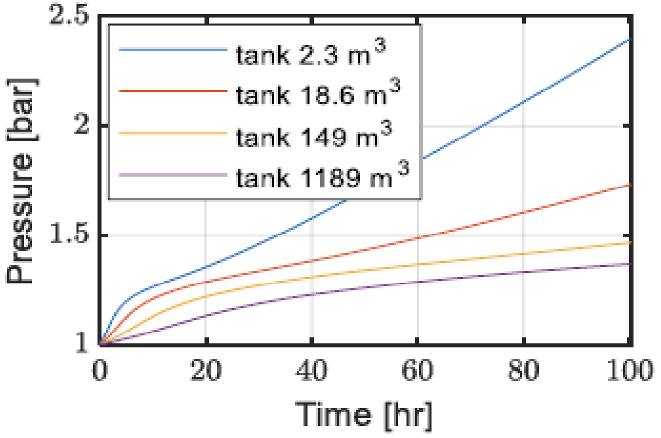
As shown, saturation temperature (and consequently the main parameter that drives the BOG rate) cannot be significantly increased by pressurizing the tank

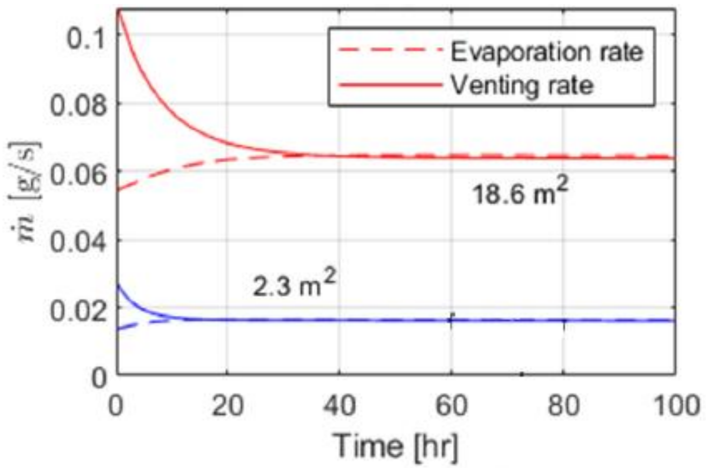


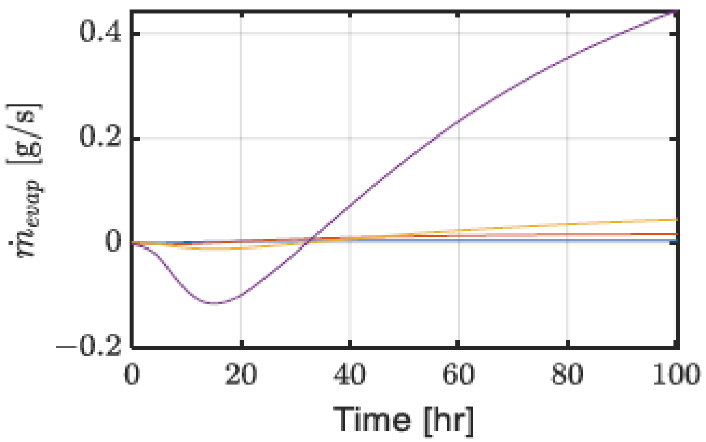
Hydrogen		Natural Gas	
Pressure [bar]	Temperature [°C]	Pressure [bar]	Temperature [°C]
1	-252,8	1	-161,6
6	-244,9	6	-134,4
10	-241,7	10	-124
12	-240,5	12	-119,9
		20	-107,3
		30	-95,8
		40	-87

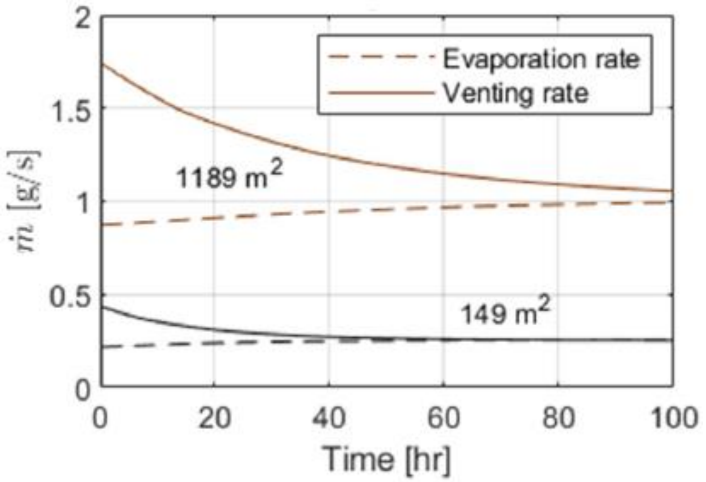


The problem of boil-off gas (BOG) - 2









As expected, the size of the tank is the most influential parameter

On such parameter depend:

- Exchange surface extension
- System's thermal capacity
- System's dynamics

Matveev and Leachmann, "*The effect of liquid hydrogen tank size on self-pressurization and constant-pressure venting*", Hydrogen, 2023

Future steps for marine green cryo-fuel

Social/economic

Development of a solid hydrogen market

Development of maritime safety regulations

Technologic

Technological transfer from LNG knowlege

Technology transfer from aerospace sector

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