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MACHINERY AND ENERGY SYSTEMS FOR THE SEA**

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**“Innovative Technologies and Low-Impact Alternative
Fuels for Maritime Sector Decarbonisation: Applicability,
Integration, Techno-Economic Assessment, and
Operational Simulations”**

Supervisors:

Prof. Ing. Loredana Magistri

Co-Supervisors:

Prof. Ing. Daria Bellotti

Candidate:

Simone Piccardo

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Abstract

In this study, ammonia is extensively analysed as an alternative zero-carbon fuel for marine applications from a techno-economic perspective. Within the framework of the green energy transition, integrating low- or zero-carbon alternative fuels into the maritime energy mix is a key strategy to comply with the long-term measures imposed by the International Maritime Organization (IMO) and governmental regulations.

Ammonia has been selected for investigation due to its zero-carbon content, favourable volumetric energy density, and lower technical challenges for onboard storage compared to cryogenic fuels such as liquefied natural gas (LNG) and liquid hydrogen. To evaluate its feasibility in maritime applications, a tailored multi-criteria approach has been developed and applied to assess the suitability of different alternative fuels across various vessel types and sizes. The results indicate that ammonia is a promising solution, particularly for ships with lower range requirements. However, the strong dependence on fuel costs has been highlighted, making the approach highly sensitive to future market scenarios.

In this regard, a comprehensive analysis of the ammonia market outlook has been conducted from different key perspectives: future blue and green ammonia production capacity, projected fuel demand, and ammonia-fuelled vessel order books, as well as the availability of port storage and bunkering infrastructure.

To further detail ammonia's implementation onboard, a multi-criteria approach alone is insufficient, as it provides only a general feasibility assessment. Given the highlighted toxicity concerns, a mathematical model has been developed to simulate the thermodynamic behaviour of the ammonia handling system's main component, represented by the storage. Following an extensive literature review on applicable modelling approaches, the Saturated Homogeneous Model (SHM) was selected for its balance between generalization potential and detailed thermodynamic representation. A flexible model was then built to simulate multiple operational conditions, including mass flow extraction for engine feeding, with the aim of analysing saturation pressure and temperature trends.

Two case studies were conducted: a 20,000 m³ Type-A tank serving a large containership and a 1,250 m³ Type-C tank for a cruise ship, both analysed under sealed and mass-flow conditions. The findings highlight scenarios where a boil-off gas (BOG) management system is necessary to control tank pressure. For the smaller tank and at high mass flow rates, a depressurization effect was observed due to evaporative cooling. This analysis underscores the high sensitivity of smaller tanks to both

self-pressurization and depressurization. However, no major critical issues were identified regarding ammonia storage.

The primary challenge associated with ammonia, its toxicity, has been further investigated through a regulatory review and subsequent risk assessment. In this context, a Formal Safety Assessment (FSA), as proposed by the IMO, was conducted for an LNG-fuelled cruise ship. This vessel type was chosen for the risk analysis due to its stringent safety requirements. Furthermore, the selection of an LNG-fuelled ship as the baseline is justified by the strong alignment between the LNG and ammonia requirements, making it a more feasible solution from a cost perspective. The results highlight potential hazards related to ammonia release in both enclosed spaces and sensitive outdoor areas, necessitating the development of mitigation measures to reduce associated risks.

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Finally, I hope that this work, along with the commitment I put into it, will prove useful and might contribute—even in a small way—to a topic I deeply care about: environmental preservation. I genuinely hope we can begin to care for our planet in a real and concrete way.

I would like to conclude with a quote that has greatly inspired me:

"Be the change that you wish to see in the world."

— *Mahatma Gandhi*

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Nomenclature

Abbreviations and Acronyms

ABS	American Bureau of Shipping
ACU	Ammonia Cracking Unit
AEGL	Acute Exposure Guideline Levels
AFC	Alkaline Fuel Cell
AFSS	Ammonia Fuel Supply System
A-FGSS	Ammonia Fuel Gas Supply System
ALARP	As Low As Reasonably Practicable
A-LFSS	Ammonia Liquid Fuel Supply System
BAC	Break-Away Coupling
BOG	Boil-Off Gas
BOR	Boil-Off Rate
BS	Bunkering Station
BSEC	Break Specific Energy Consumption
BSFC	Break Specific Fuel Consumption
BV	Bureau Veritas
CFD	Computational Fuel Dynamic
CH ₂	Compressed Hydrogen
CH ₄	Methane
CI	Compression Ignition
CO ₂	Carbon Dioxide
CTP	Climate Target Plan
DF	Dual Fuel
D/G	Diesel Generator
DMFC	Direct Methanol Fuel Cell
DNV	Det Norske Veritas
DWT	Deadweight Tonnage
ERC	Emergency Release Coupling
ETS	Emissions Trading System
FO	Fuel Oil

FPR	Fuel Preparation Room
FSA	Formal Safety Assessment
GHG	Green House Gas
GT	Gross Tonnage
H ₂	Hydrogen
HAZID	HAZard IDentification
HELM	Helper for Energy Layouts for Maritime applications
HFO	Heavy Fuel Oil
ICE	Internal Combustion Engine
IMO	International Maritime Organization
LCA	Life Cycle Assessment
LH ₂	Liquefied Hydrogen
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
LP	Low Pressure
LR	Lloyd's Register
LT-PEMFC	Low Temperature Proton Exchange Membrane Fuel Cell
HT-PEMFC	High Temperature Proton Exchange Membrane Fuel Cell
MARVS	Maximum Allowable Relief Valve Setting
MCR	Maximum Continuous Rating
MDO	Marine Diesel Oil
MeOH	Methanol
MEPC	Marine Environmental Protection Committee
MGO	Marine Gas Oil
MH	Metal Hydrides
MSHM	Modified Saturated Homogeneous Model
N ₂	Nitrogen
NFPA	National Fire Protection Association
NG	Natural Gas
NH ₃	Ammonia
NO _x	Nitrogen Oxides
NRC	National Research Council
NTEM	Non-Thermal Equilibrium Model

OSHA	Occupational Safety and Health Administration
PAFC	Phosphoric Acid Fuel Cell
PEL	Permissible Exposure Limit
PR-EOS	Peng-Robinson Equation Of State
PRV	Pressure Relief Valve
PU	Power Unit
QCDC	Quick Connect/Disconnect Coupling
RCM	Risk Control Measure
RCO	Risk Control Option
RINA	Registro Italiano NAVale
RMFC	Reformed Methanol Fuel Cell
SHM	Saturated Homogeneous Model
SI	Spark Ignition
SCR	Selective Catalytic Reductor
SEM	Surface Evaporated Model
SOFC	Solid Oxide Fuel Cell
SR	Substitution Rate
SRtP	Safe Return to Port
TCS	Tank Connection Space
TEM	Thermal Equilibrium Model
TEU	Twenty-foot Equivalent Unit
THS	Tank Hold Space
TMNM	Thermal Multi-Node Model
TMZM	Thermal Multi-Zone Model
TSM	Thermal Stratified Model
TtW	Tank to Wake
WtW	Well to Wake

Main Variables

Symbol	Unit	Name
A_S	[m ²]	Vapour-liquid interface area
BOR	[kg/h]	Boil-off Rate
$BSEC$	[kJ/kWh]	Break specific energy consumption
$BSFC$	[kg/kWh]	Break specific fuel consumption
FL	[%]	Filling limit
g	[m/s ²]	Gravity acceleration
Gr	[-]	Grashof number
h	[W/m ² /K]	Convective heat transfer coefficient
h_{liq}	[kJ/kg/K]	Liquid specific enthalpy
h_{vap}	[kJ/kg/K]	Vapour specific enthalpy
k	[W/m/K]	Conductive heat transfer coefficient
k_{ins}	[W/m/K]	Tank insulation conductive heat transfer coefficient
LHV	[MJ/kg]	Lower heating value
LL	[%]	Loading Limit
$\dot{m}_{engine}$	[kg/h]	Mass flow rate required by the engines
$\dot{m}_{evap}$	[kg/h]	Evaporated mass flow rate
M_{liq}	[kg]	Liquid mass within the storage tank
$\bar{M}_{liq}$	[-]	Normalized liquid mass within the storage tank
M_{tot}	[kg]	Total mass within the storage tank
M_{vap}	[kg]	Vapour mass within the storage tank
Nu	[-]	Nusselt number
p_{in}	[Pa]	Initial saturation pressure
P_{MCR}	[kW]	Power at maximum continuous rating
Pr	[-]	Prandtl Number
P_S	[m]	Vapour-liquid interface perimeter
p_{sat}	[Pa]	Saturation pressure
$\dot{q}_{ext}$	[kJ/h]	Heat flow entering within the storage

Symbol	Unit	Name
Ra	[-]	Rayleigh number
R_i	[-]	Relevance of the i -th key parameter
S_{ij}	[-]	Score for the i -th key parameter and the j -th technology
SR	[%]	Substitution rate
S_{tank}	[m ²]	Tank lateral surface
S_{tot}	[-]	Total score
T_{ext}	[K]	External temperature
th_{ins}	[m]	Tank insulation thickness
T_{in}	[K]	Initial saturation temperature
T_R	[K]	Reference temperature
T_{sat}	[K]	Saturation Temperature
T_{∞}	[K]	Temperature at an infinite distance from the surface
u_{liq}	[kJ/kg]	Specific internal energy of the liquid
u_{mix}	[kJ/kg]	Specific internal energy of the vapour-liquid mixture
u_{vap}	[kJ/kg]	Specific internal energy of the vapour
$\dot{v}_{engine}$	[m ³ /h]	Volumetric flow rate required by the engines
v_{liq}	[m ³ /h]	Specific volume of the liquid
$\bar{v}_{liq}$	[-]	Normalized specific volume of the liquid
v_{mix}	[m ³ /kg]	Specific volume of the vapour-liquid mixture
V_{net}	[m ³]	Net volume within the storage tank
V_{tot}	[m ³]	Total volume within the storage tank
v_{vap}	[m ³ /kg]	Specific volume of the vapour
x	[-]	Quality of the vapour-liquid mixture
α	[m ² /s]	Thermal diffusivity
Δt	[h]	Simulation timestep
ν	[m ² /s]	Kinematic Viscosity
ρ_L	[kg/m ³]	Relative Density of fuel at the loading temperature
ρ_{liq}	[kg/m ³]	Density of the liquid

ρ_{mix}	[kg/m ³]	Density of the vapour-liquid mixture
Symbol	Unit	Name
ρ_R	[kg/m ³]	Relative Density of fuel at the reference temperature
ρ_{vap}	[kg/m ³]	Density of the vapour
φ	[%]	Filling level
φ_0	[%]	Initial filling

1. Introduction and Motivation.

Within the context of the green energy transition and considering the negative effects of climate change, it is essential to develop either new technologies and concrete governmental actions to reduce greenhouse gas emissions resulting from human activities. One of the greatest challenges of this century is ensuring the conservation of biodiversity and the global ecosystem, protecting human health, and preventing significant socio-economic issues associated with climate change.

In this perspective, foresight is a key principle that must be effectively applied to establish a consistent framework aimed at reducing the environmental impact of human activities. Therefore, research and development of alternative technologies are crucial steps in identifying economically and technically viable solutions across a broad range of possibilities.

From a transportation perspective—one of the most significant sources of pollutant emissions—this work aims to gather valuable information and deepen techno-economic studies on maritime sector decarbonization. Although the maritime sector represents a smaller share of transport-related GHG emissions, it is essential to pursue decarbonization efforts to accelerate a broader energy transition.

The use of alternative low- or zero-carbon fuels as onboard energy storage is one of the key pathways being pursued, alongside efforts to reduce ship energy consumption. This study specifically focuses on the first approach, emphasizing the need for a comprehensive techno-economic feasibility assessment.

In this context, it is essential to have either a broad overview of all viable alternatives, understand future market projections, and analyse the technical aspects of the most promising technologies. This justifies the implementation of a preliminary comparative approach.

Specifically, this work focuses on ammonia as an alternative fuel. This choice was made due to its strong potential in the maritime decarbonization scenario. In fact it meets the zero-carbon requirement—aligning with long-term sustainability measures—while presenting fewer technical challenges in handling compared to hydrogen. However, due to its toxicity, it is crucial to strongly emphasize the simulation of onboard system behaviour under potential operating conditions, as well as human safety, treated as a mandatory requirement.

Regarding the first objective, this study highlights the importance of developing predictive models to identify critical situations within the storage system, which is a key component for large vessels.

The second main objective, safety assessment, remains essential. Therefore, a regulated framework based on risk analysis plays a crucial role in ensuring safe implementation.

A comprehensive techno-economic assessment is therefore essential to make decisions regarding both the feasibility and the suitability of a given technology. However, a conclusive and universally applicable solution cannot be selected within this context, as several uncertainties remain regarding future economic and governmental scenarios, which can affect both its feasibility and applicability. Operational requirements also play a fundamental role in the final decision, as different vessels require different operational conditions. Therefore, the final resolution remains highly dependent on technical factors, following a case-by-case approach.

Nonetheless, understanding the contextual behaviour of a technology is crucial for drawing future decisions, as it represents the core of research and development activities.

2. Global Scenario.

This chapter provides a comprehensive overview of the global scenario from multiple perspectives. In a context where climate change is a pressing issue and the energy transition is imperative, the maritime sector is also striving for a greener future. This scenario underscores the need for a broad perspective, encompassing both strategic actions and technical approaches, to achieve maritime decarbonization.

In this chapter, key governmental and organizational measures are summarized, beginning with the perspective of the International Maritime Organization (IMO) and subsequently examining major governmental strategies.

From a technical standpoint, two main approaches can be adopted to reduce the maritime sector's environmental impact: enhancing energy efficiency through the implementation of various technologies and optimized operational practices, and adopting alternative low-carbon fuels. This study specifically focuses on alternative fuels, providing an overview of their key characteristics using a Well-to-Wake (WtW) approach.

With a particular emphasis on ammonia as a potential alternative fuel, the market scenario is analysed from three key perspectives to assess the actual interest in its adoption: future fleet demand, bunkering and storage availability in ports, and projected production capacity.

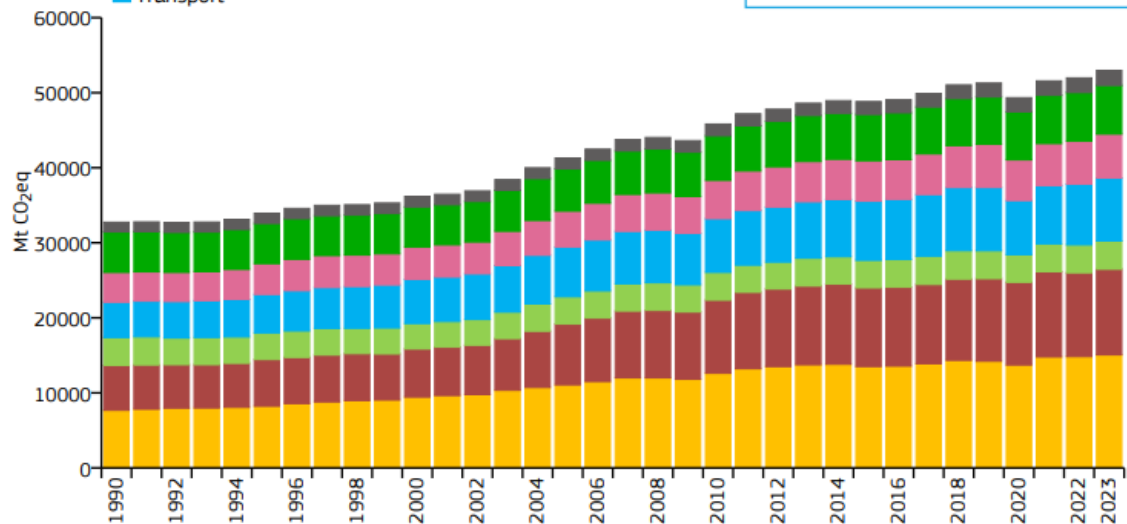
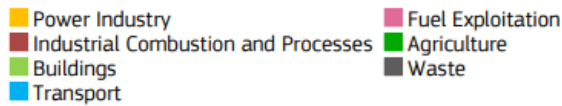
Climate change is one of the most pressing issues of this century, requiring urgent and substantial action to mitigate the rise in global average temperatures and its consequent negative impacts on the climate, society, and the economy.

As the EU's Emissions Database for Global Atmospheric Research (EDGAR) reports ([Figure 1](#)) [1], the latest data, updated to 2023, indicate a continued rise in global greenhouse gas (GHG) emissions from 1990 to 2023, reaching approximately 50 Gtons of CO₂ equivalent by the end of 2023. Carbon dioxide (CO₂) remains the predominant GHG, accounting for 73.7% of total emissions, followed by methane (CH₄) and nitrous oxide (N₂O).

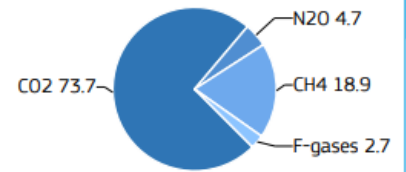
The largest contributor to global GHG emissions is the power industry sector, which accounted for more than 20% of total emissions in 2023. Other significant sources include industrial combustion/processes and the transportation sector.

WORLD

GHG emissions by sector



GHG % in 2023



Year	GHG emissions Mt CO ₂ eq/yr	GHG emissions per capita t CO ₂ eq/cap/yr	GHG emissions per unit of GDP PPP t CO ₂ eq/kUSD/yr	Population
2023	52962.901	6.594	0.320	8.032G
2015	48808.767	6.613	0.369	7.381G
2005	41296.885	6.314	0.437	6.540G
1990	32726.228	6.140	0.543	5.330G

2023 vs 1990

2023 vs 2005

2023 vs 2022

	Power Industry	↗ +96%	↗ +36%	→ +2%
	Industrial Combustion and Processes	↗ +91%	↗ +41%	→ +2%
	Buildings	→ +1%	→ +3%	→ +1%
	Transport	↗ +78%	↗ +26%	→ +4%
	Fuel Exploitation	↗ +48%	↗ +23%	→ +2%
	Agriculture	↗ +20%	↗ +15%	→ 0%
	Waste	↗ +56%	↗ +37%	→ +2%
	All sectors	↗ +62%	↗ +28%	→ +2%

Figure 1: Worldwide GHG emissions over time

As reported in [Figure 2](#) [2], within the transportation sector, road transport has the greatest impact, accounting for nearly 72% of total emissions in the European Union in 2023. In contrast, the shipping sector in the same region contributes a significantly lower, yet still notable, share of 14.1%. Therefore, targeted actions are necessary to support the global energy transition and mitigate emissions from these sectors.

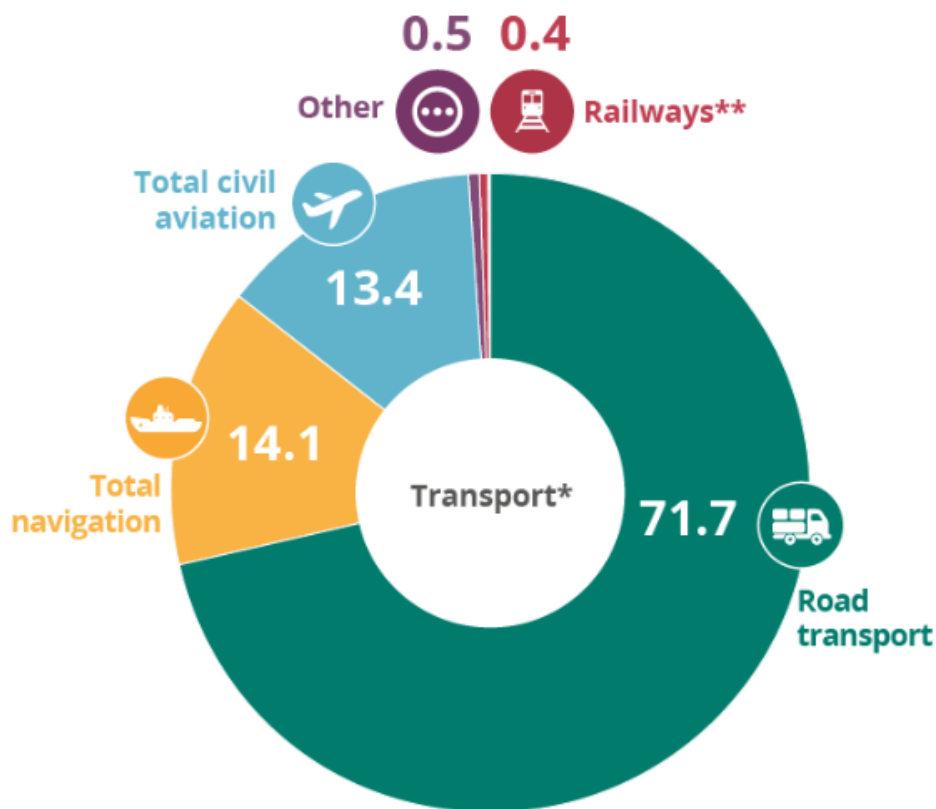


Figure 2: GHG emissions share from the transportation sector within the European Union.

2.1. Strategies and Regulations in the Maritime Sector.

As outlined in the preceding scenario, it is essential to take action to reduce global emissions from the maritime sector. To achieve this objective, the International Maritime Organization (IMO) and various governments have established specific targets aimed at steering the maritime industry towards complete decarbonization. Therefore, to gain insight into the current global perspectives, a policy research study has been conducted from the viewpoints of the IMO and different major governments, including the EU, US, China, and Japan.

In particular, the IMO has developed strategies to address emissions reduction for sulphur oxides (SO_x), nitrogen oxides (NO_x), and greenhouse gases (GHG). Regarding SO_x and NO_x, which are byproducts of fuel combustion, these pollutants pose significant risks to human health. To mitigate their impact, Emissions Control Areas (ECAs) [3] have been designated globally ([Figure 3](#)), within which SO_x and NO_x emissions are subject to stringent limitations.

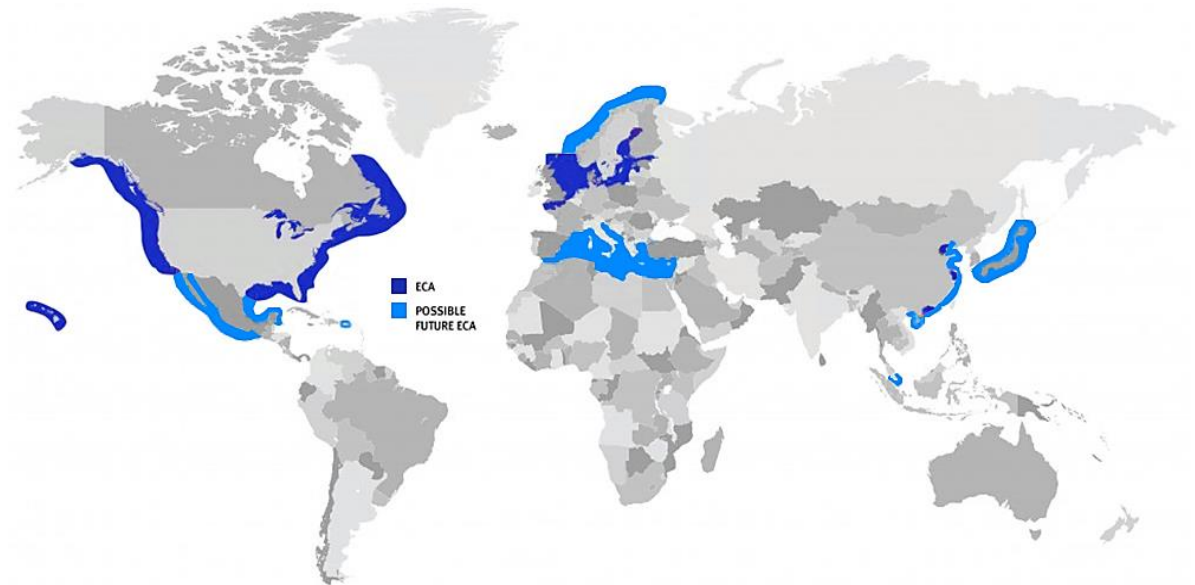


Figure 3: Worldwide ECAs

Specifically for NO_x, emission limits have been defined based on the rated speed of internal combustion engines (ICE), with distinct trends (Tier I, Tier II, and Tier III) [3] illustrated in [Figure 4](#). These limits differentiate between global standards and standards applied within ECAs, with the latter achieving substantial reductions in NO_x emissions.

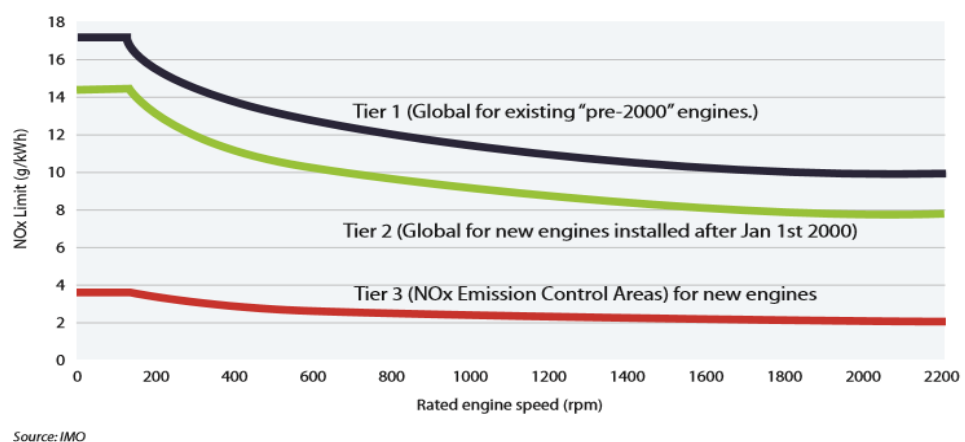


Figure 4: Tier 1,2, and 3 trends on NO_x emissions

SOx emissions are regulated through temporal trends that mandate a reduction in fuel sulphur content (*Figure 5*), addressing both global standards and the stricter requirements within ECAs.

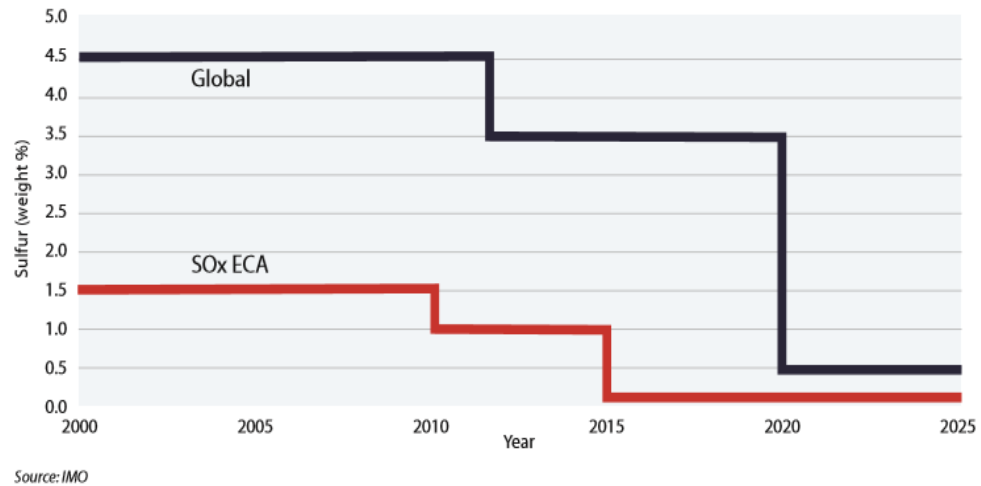


Figure 5: Limits on fuel sulphur content over the years

Considering GHG emissions, the IMO's Marine Environmental Protection Committee (MEPC) completed the first revision of its strategies in July 2023 and subsequently updated them [4]. The revised strategies, establish following indicative checkpoints:

- Well-to-Wake (WtW) GHG emissions reduction by 20%, striving for 30%, by 2030 (2008 as baseline);
- WtW GHG emissions reduction by 70%, striving for 80%, by 2040 (2008 as baseline);
- Reach net-zero “by or around” 2050 (2008 as baseline);
- At least 5%, striving for 10%, of energy used by international shipping provided by zero or near-zero GHG emissions technologies, fuels and/or energy sources, by 2030.

To achieve the aforementioned targets, the IMO has established three types of measures:

- **Short-term Measures** [5] [6]

This set of measures defines Carbon Intensity Indicator (CII), Energy Efficiency Existing Ship Index (EEXI) and Ship Energy Efficiency Management Plan (SEEMP), focusing on energy efficiency but without any prescription on the fuel type.

- **Mid-term Measures** [6] [4]

A basket of measures is in phase of implementation, consisting of two parts: technical and economic. The first one will be a goal-based marine fuel standard regulating the phased reduction of marine fuel GHG intensity. While the second part will be some form of maritime GHG emissions pricing mechanism, potentially linked directly to the GHG-intensity mechanism. Further mid-term strategies include development of feedback mechanisms on implementations of measures, further development on Life Cycle Assessment (LCA) guidelines, incentives for new technologies, etc...

- **Long-term Measures** [6]

Regarding long term measures, finalizing the net-zero pathway, they still need to be defined to meet long-term goals.

The IMO strategy described above is illustrated in **Figure 6**, which outlines the timeline up to 2030.

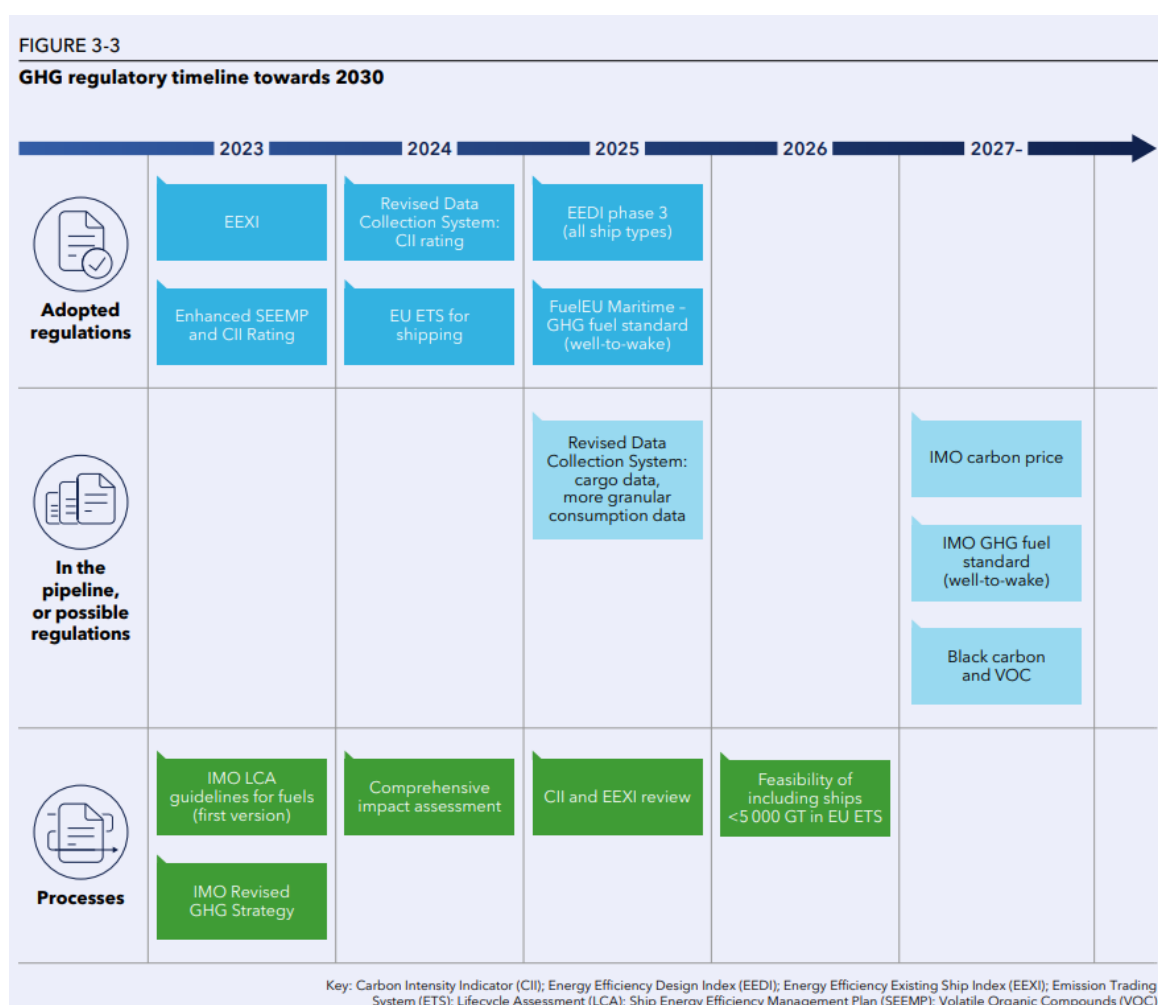


Figure 6: IMO regulatory timeline towards 2030

From the European Union point of view, to achieve climate neutrality in 2050, a 90% reduction in transport emissions is needed by 2050 [7]. All transport modes, including maritime transport, will have to contribute to the reduction efforts. In this scenario, concerning shipping, EU identifies different measures to push towards the previous requirements achieving:

- Revision of the EU ETS, defining a carbon levy, include shipping from 2024.
- FuelEU Maritime has been adopted by EU to increase the share of renewable and low-carbon fuels in maritime transport in the EU. Depending on the policy scenarios assessed in the framework of the 2030 Climate Target Plan (CTP) and in support of the Sustainable and Smart Mobility Strategy, previous fuels should represent between 6% and 9% of the international maritime transport fuel mix in 2030 and between 86% and 88% by 2050 to contribute to the initially indicated EU economy-wide GHG emissions reduction targets [8]. Goals will ensure that the greenhouse gas intensity of fuels used in the sector will gradually decrease over time, starting with a 2% decrease by 2025 and reaching up to an 80% reduction by 2050 [9]. These targets cover not only CO₂ but also methane and nitrous oxide emissions over the full lifecycle of the fuels used onboard, on a Well-to-Wake (WtW) basis [9].

Differently by the EU, US has not enshrined a climate target in its national laws, but similar targets have been set [10]:

- From a 50% to 52% reduction in net GHG emissions by 2030;
- Long-term strategy to achieve net-zero emissions by 2050.

Furthermore, US has initiated several key shipping initiatives such as the “*First Mover Coalition*” [11] and the “*Green Shipping Challenge*” [12]. The first one sets targets on the employment of zero-emissions technology on board while the second one aims to study, promote, and develop production of zero-emissions fuels, zero-emissions vessels and launch advancement of green shipping corridors.

By means of different funding and projects Japan aims to meet similar targets on GHG emissions reduction, reported below [13]:

- 45% reduction on GHG emissions by 2030 (2013 used as baseline)
- Carbon neutrality by 2050.

In order to achieve previous targets Japan laying out action plans in 14 priority sectors, including hydrogen and ammonia.

Concerning China [7], *China's Ministry of Transport* published the 14th Five-Year Plans, one for the *Development of Green Transport* and another for *Waterway Transport* in January 2022. These plans encourage the application of new and clean energy including LNG, methanol, hydrogen, ammonia, as well as the increased use of shore power.

Regarding market-based measures, China's national *ETS* started operating in 2021 and is presently covering power production only. The planned expansion of the *ETS* into seven new sectors does not include shipping.

2.2. Alternative Fuels and Technologies for Sector Decarbonization Strategies and Regulations in the Maritime Sector.

In the scenario described above, it is crucial to identify the most effective solutions for reducing the environmental impact of the maritime sector. In this context, two main approaches can be considered: enhancing energy efficiency through the implementation of various technologies or optimized operational practices, and adopting alternative low-carbon fuels. These measures should not be viewed in a de-coupled way, as their combined implementation can contribute to defining an optimal working scenario, which must be evaluated on a case-by-case basis.

Specifically, this study focuses on alternative fuels as a means of decarbonization; therefore, it is essential to provide an overview of the main characteristics, advantages and disadvantages of the alternative fuels expected to lead the market.

2.2.1. Liquefied Natural Gas (LNG).

Liquefied Natural Gas (LNG) is the widely spread marine alternative fuel, accounting for more than 1,239 operating vessels in 2025, as the *DNV Energy Transition Outlook* [14] reports. Specifically LNG-fuelled ships represent 6.7% of the tonnage for ships in operation, while 36% of the tonnage in the order book can use LNG as fuel. It remains a popular solution mainly in the containerships and car carrier segment but significant uptakes have been registered on bulk carriers, cruise ship and tanker. Main part of LNG-fuelled fleet is represented by LNG carriers, using their own cargo as fuel. LNG is primarily composed of methane (CH_4), with smaller percentages of ethane, propane, butane, and other minor components, depending on its place of extraction [15].

From a chemical point of view, main features are reported in [Table 1](#). From this table it is possible to note that an higher Lower Heating Value (LHV) is reached by NG, overcoming both the

MDO/MGO and HFO values: 40.2 MJ/kg and 42.7 MJ/kg [16], respectively. This means that NG achieves higher gravimetric energy density than conventional fuels. However, even if the storage temperature is -162 °C, resulting in costly storage system, its density is of about half of MDO. This results in a lower volumetric energy density, leading to increased spaces to store the same energy amount.

LNG Main Characteristics	
Main Components	CH ₄ ; C ₂ H ₆ ; C ₃ H ₈ ; C ₄ H ₁₀
Boiling Temperature (1 bar)	-162 °C
Autoignition Temperature	537 °C
LHV	49.2 MJ/kg
Density (-162 °C)	450 kg/m ³
Vol. En. Density (-162 °C)	22.1 MJ/dm ³
Flammability Range	5 – 14% vol. in air
Main Hazards	• Flammability • Cryogenic fluid

Table 1: Key Chemical and Physical Properties of LNG and Associated Hazards

Considering safety issues, the classification by the National Fire Protection Association (NFPA) [17] distinguishes different hazard classes, as highlighted in [Figure 7](#) [18]. In [Figure 8](#), the hazard classes assigned to LNG are represented, following the LNG datasheet indications [19]. The main concerns regarding this fuel are primarily related to its flammability, which reaches the highest hazard category, and its potential risks to human health due to its cryogenic storage temperature.

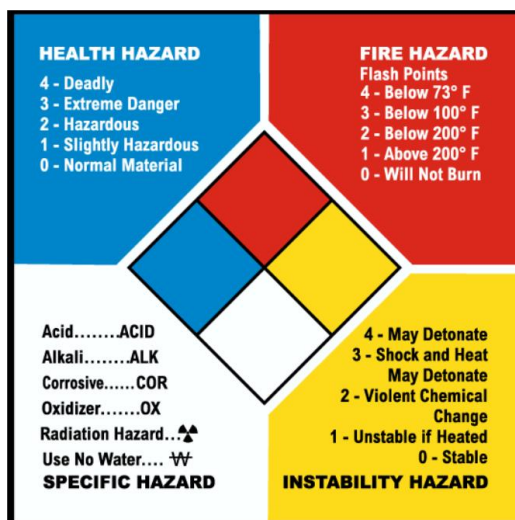


Figure 7: NFPA classification of Hazards and intensity levels



Figure 8: NFPA hazard levels for LNG

As highlighted in [Table 2](#), on-board ships, LNG is primarily used in Dual-Fuel Internal Combustion Engines, both 2-stroke (2-ST) and 4-stroke (4-ST), which are capable of meeting high power demands. The LNG-fuelled ICE market is well established, offering a variety of products from different manufacturers.

Another technology capable of utilizing LNG as fuel is solid oxide fuel cells (SOFC), which can achieve high electrical efficiencies (50-60%) [20]. However, this technology is not yet available in sizes large enough to cover the required power range and is not widely adopted, particularly in maritime applications, where operational constraints pose additional challenges for this type of fuel cell. Nevertheless, it remains an interesting area of study for future developments in the maritime sector.

LNG Usable Converters
• 4-ST CI DF-ICE – 4 Stroke Compression Ignition Dual Fuel Internal Combustion Engines • 2-ST CI DF-ICE – 2 Stroke Compression Ignition Dual Fuel Internal Combustion Engines • 4-ST SI ICE – 4 Stroke Spark Ignition Internal Combustion Engines • SOFC – Solid Oxide Fuel Cells

Table 2: Suitable PU using LNG as fuel

[Figure 9](#) presents the main NG production methods, highlighting its carbon intensity. It is important to note that NG is primarily extracted from fossil feedstocks, which currently represents the main process for obtaining LNG.

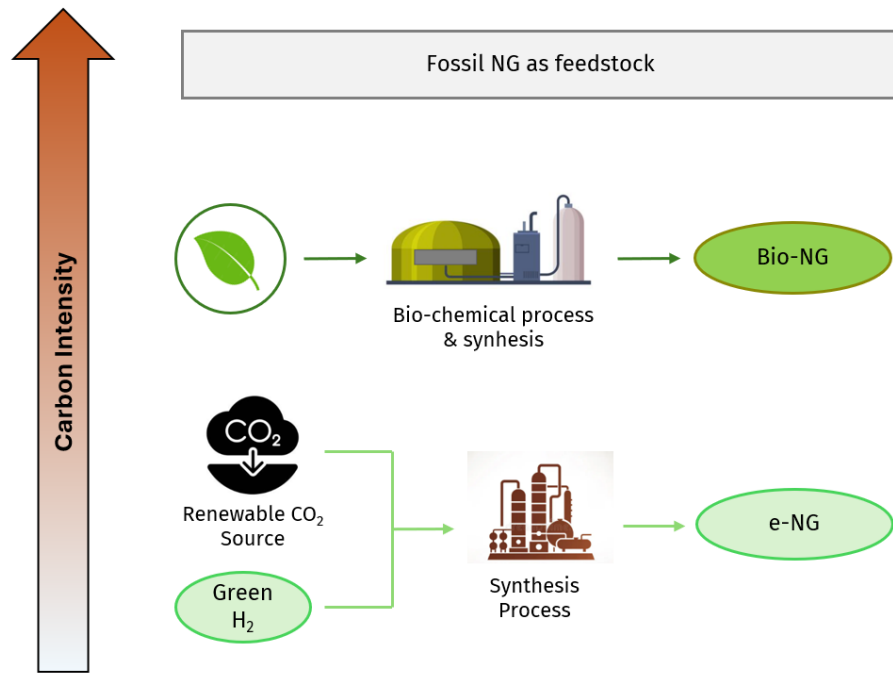


Figure 9: NG production pathways representation

2.2.2. Methanol (MeOH).

Methanol is one of the most promising alternative fuel solutions. It is an alcohol that remains liquid at ambient temperature and pressure, allowing for easy storage. According to the *DNV Energy Transition Outlook* [14] methanol-fuelled ships currently account for only 0.09% of the global fleet tonnage in operation but represent 9.68% of the tonnage on order. The containership segment experienced a significant increase in methanol-fuelled ship orders during 2023. Additionally, bulk carriers and car carriers have recently entered methanol-related shipping statistics.

As shown in [Table 3](#), MeOH has a LHV approximately half that of HFO, resulting in a low gravimetric energy density. However, its good density allows for better performance in terms of volumetric energy density, although still lower than that of conventional fuels.

As highlighted in [Figure 10](#) [21], methanol presents certain hazards according to NFPA standards, particularly in terms of flammability and, to a lesser extent, toxicity. It is classified as a low flash-point fuel.

MeOH Main Characteristics	
Chemical Formula	CH ₃ OH
Boiling Temperature (1 bar)	65 °C
Autoignition Temperature	470 °C
LHV	19.9 MJ/kg
Density	790 kg/m ³
Vol. En Density	15.7 MJ/ dm ³
Flammability Range	6 – 36.5 % vol. in air
Main Hazard	• Flammability • Toxicity



Table 3: Key Chemical and Physical Properties of MeOH and Associated Hazards

Figure 10: NFPA hazard levels for MeOH

Due to methanol's high autoignition temperature, a high compression ratio would be required if used in a CI-ICE without a pilot fuel. Consequently, the use of a pilot fuel in a dual-fuel engine is the preferred approach. Different products are already present on the market achieving high powers.

Additionally, reformed methanol fuel cells (RMFC) [22] [23] and direct methanol fuel cells (DMFC) [23] are technologies currently under development. RMFC technology involves the integration of a methanol reforming unit with a high-temperature proton exchange membrane fuel cell (HT-PEMFC). In this process, hydrogen is extracted from methanol through a reforming reaction and subsequently oxidized in the HT-PEMFC. The higher operating temperatures of this type of fuel cell make it less sensitive to carbon-based byproducts from the reforming process. RMFC represents a promising new technology for maritime applications; however, the achievable power output currently does not exceed 250 kW per module [24].

DMFC technology allows methanol to be used directly in a low-temperature proton exchange membrane fuel cell (LT-PEMFC), where materials particularly sensitive to carbon-based byproducts are replaced with less sensitive alternatives. However, this results in lower efficiency and relatively short lifetimes. Additionally, the achievable power output remains strictly limited to small-scale applications [23] [25] .

As described above, [Table 4](#) groups main usable power unit when MeOH is considered as fuel.

MeOH Usable Converters
• 4-ST CI DF-ICE – 4 Stroke Compression Ignition Dual Fuel Internal Combustion Engines • 2-ST CI DF-ICE – 2 Stroke Compression Ignition Dual Fuel Internal Combustion Engines • RMFC – Reformed Methanol Fuel Cells • DMFC – Direct Methanol Fuel Cells

Table 4: Suitable PU using MeOH as fuel

Figure 11 highlights the main MeOH production processes and the associated carbon intensity trends.

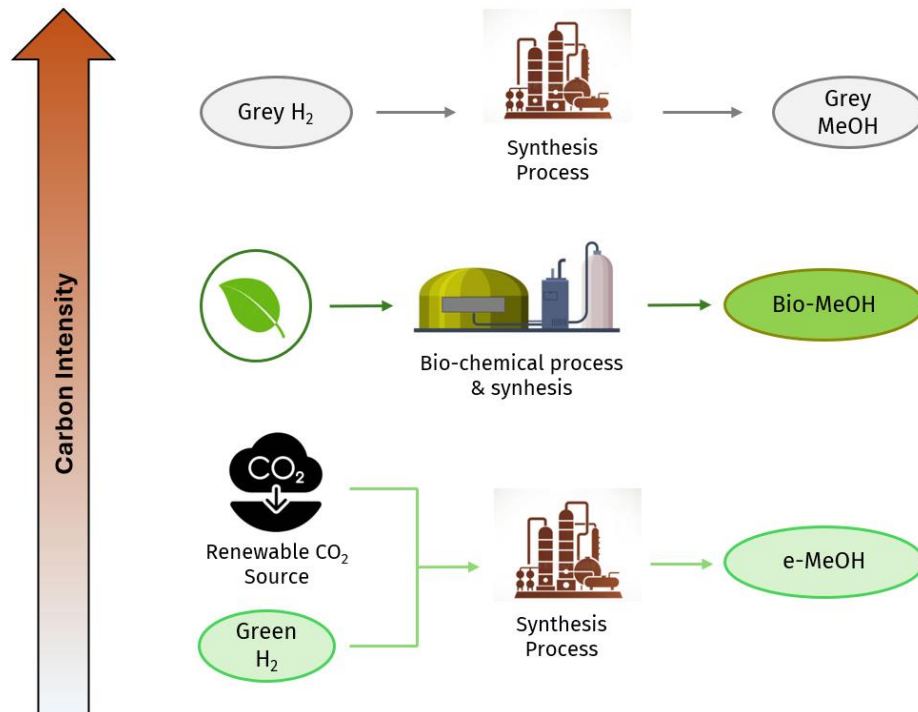


Figure 11: MeOH production pathways representation

2.2.3. Hydrogen (H₂).

Although hydrogen is one of the key components for decarbonizing the maritime sector, its direct application as an alternative fuel remains limited to small-scale uses that do not require significant energy storage, as stated in the *DNV Energy Transition Outlook* [14]. This scenario is primarily driven by hydrogen's low energy density. Despite its very high lower heating value (LHV), liquid hydrogen (LH₂) can only achieve a storage density of 71 kg/m³ at -253°C. Therefore, even in its liquid state, hydrogen's energy density remains limited (as shown in [Table 5](#)), falling well below that

of conventional fuels. Furthermore, maintaining such cryogenic temperatures presents significant technical challenges.

As highlighted in [Table 5](#), [Figure 12](#) [26], and [Figure 13](#) [27], the main hazard associated with hydrogen is its high flammability, placing it in the most dangerous category. However, when considering LH₂ ([Figure 12](#)), health hazards also become significant due to its extremely low storage temperature. On the other hand, when evaluating hydrogen as a substance without considering its storage method, gaseous H₂ does not pose health risks, as it is non-toxic ([Figure 13](#)).

H ₂ /LH ₂ Main Characteristics	
Chemical Formula	H ₂
Boiling Temperature (1 bar)	-253 °C
Autoignition Temperature	500 °C
LHV	120 MJ/kg
Density (-253 °C)	71 kg/m ³
Vol. En Density (-253 °C)	8.5 MJ/ dm ³
Flammability Range	4 – 75 % vol. in air
Main Hazard	• Flammability • Cryogenic fluid (LH₂)

Table 5: Key Chemical and Physical Properties of H₂/LH₂ and Associated Hazards



Figure 12: NFPA hazard levels for LH₂



Figure 13: NFPA hazard levels for gaseous H₂

As highlighted in [Table 6](#), in marine applications, the use of both fuel cells and ICE are applicable [28]. According to information from various providers, ICEs can run on either pure hydrogen or with a hydrogen-MGO blend [29]. However, only a few products are currently available, and they offer limited power outputs.

Fuel cells, where hydrogen serves as the primary fuel, present significant potential. Among the various types of fuel cells, LT-PEMFC stand out as the most promising solution for maritime applications due to their high efficiencies (45-55%) [20], rapid start-up times, relatively long lifetimes, and greater flexibility when compared to other fuel cell technologies like SOFC.

Despite the high TRL of LT-PEMFCs and the availability of marinized products on the market, their onboard application remains limited.

The achievable power currently reaches 225 kW per module [30]. However, several projects focusing on the scale-up of LT-PEMFC systems are underway, aiming to achieve power outputs exceeding 1 MW [31] [32].

H₂ Usable Converters
• ICE - Internal Combustion Engine (General) • LT-PEMFC - Low-Temperature Proton Exchange Membrane Fuel Cells • HT-PEMFC - High-Temperature Proton Exchange Membrane Fuel Cells • SOFC – Solid Oxide Fuel Cells • PAFC – Phosphoric Acid Fuel Cell • AFC – Alkaline Fuel Cell

Table 6: Suitable PU using H₂ as fuel

Figure 14 highlights the main H₂ production processes and their associated carbon intensity.

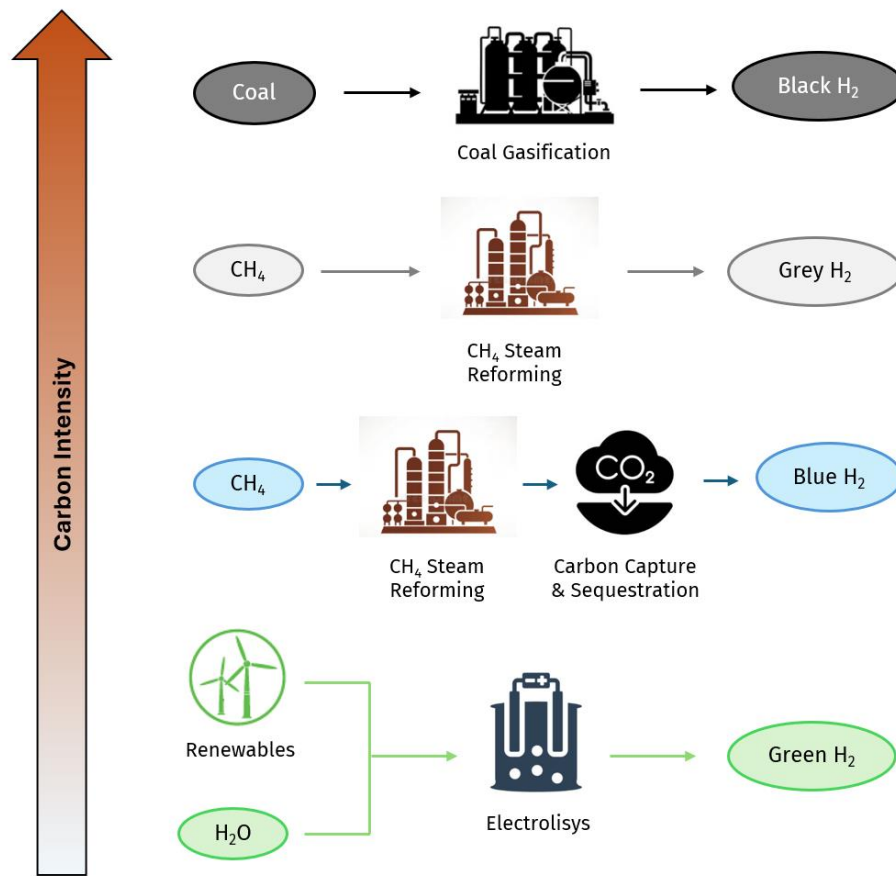


Figure 14: H₂ production pathways representation

2.2.4. Ammonia (NH₃).

Ammonia is considered one of the best candidates for marine alternative fuel in the long term, primarily due to its completely carbon-free nature. According to the *DNV Energy Transition Outlook* [14], the first orders for ammonia-fuelled ships have recently been placed. Specifically, eight bulk carriers with main engines capable of operating on ammonia have been added to the order book. Additionally, ammonia carriers, which burn their own cargo as fuel, could see significant development as pioneering ammonia-fuelled vessels. Currently, only 2 operating vessels [33] are able to burn either ammonia and MGO as fuels, using a DF ICE, as highlighted in [34].

As shown in [Table 7](#), ammonia has lower energy densities, both because of its reduced LHV and its moderate gravimetric density. However, ammonia's storage is technically simpler due to its non-cryogenic temperature requirements. The complete absence of CO₂ in its combustion process is a notable advantage, particularly in a scenario where carbon levies are high. Nevertheless, attention must be given to the potential emissions of N₂O, NO_x, and NH₃ leakages, especially if an ICE is used as a converter.

Regarding safety hazards, as illustrated in [Figure 15](#) [35], ammonia presents several health-related risks due to its high toxicity. In terms of flammability, however, the concerns associated with this fuel are relatively limited.

NH₃ Main Characteristics	
Chemical Formula	NH ₃
Boiling Temperature (1 bar)	-33 °C
Autoignition Temperature	652 °C
LHV	18.7 MJ/kg
Density (-33 °C)	682 kg/m ³
Vol. En. Density (-33°C)	12.7 MJ/ dm ³
Flammability Range	15 – 28 % vol. in air
Main Hazard	• Flammability • Toxicity



Table 7: Key Chemical and Physical Properties of NH₃ and Associated Hazards

Figure 15: NFPA hazard levels for NH₃

To highlight the main concerns regarding ammonia toxicity, particularly when integrating it onto sensitive types of ships, [Table 8](#) presents the Acute Exposure Guideline Levels (AEGL) for ammonia [36], managed by the *Environmental Protection Agency* (EPA) and the *United States National Research Council* (NRC). According to the AEGL program, the following distinctions are made:

- AEGL1: A situation in which there are no negative effects on human health.
- AEGL2: A situation where exposure could potentially lead to severe or irreversible health effects.
- AEGL3: A situation where potentially fatal effects could occur.

These scenarios are coupled with specific ammonia concentration limits that correspond to different exposure times.

	10 min	30 min	60 min	4 hr	8 hr
ppm					
AEGL 1	30	30	30	30	30
AEGL 2	220	220	160	110	110
AEGL 3	2,700	1,600	1,100	550	390

Table 8: AEGL NH₃ exposure limits and related concentrations

When considering the use of ammonia as a fuel in marine applications, the primary focus is on ICE. Leading providers have already commercialized both 4-ST and 2-ST engines, although the overall number of available alternatives remains somewhat limited.

SOFCs, directly fed by ammonia [37], present another promising solution. However, these are still in the early stages of development, identifying low TRL. While several studies on operability have shown promising results, there is still a significant gap in durability testing.

More conventional fuel cells, such as LT and HT-PEMFCs, can also be used as converters for ammonia. In this case, an Ammonia Cracker Unit (ACU) is required to facilitate the ammonia cracking process, extracting H₂ to be supplied to the fuel cell stacks. This setup introduces additional complexities to the system, as marinized cracker reactors are still lacking optimized solutions for marine applications [38].

Table 9 summarizes the previously highlighted considerations regarding potential power units.

NH₃ Usable Converters
• 2-ST DF ICE - Internal Combustion Engine (General) • 4-ST DF ICE - Low-Temperature Proton Exchange Membrane Fuel Cells • SOFC – Solid Oxide Fuel Cells • Other FC + ACU – Other Fuel Cell Type coupled wit Ammonia Cracking Units

Table 9: Suitable PU using NH₃ as fuel

Figure 16 highlights the main NH₃ production processes and their associated carbon intensity.

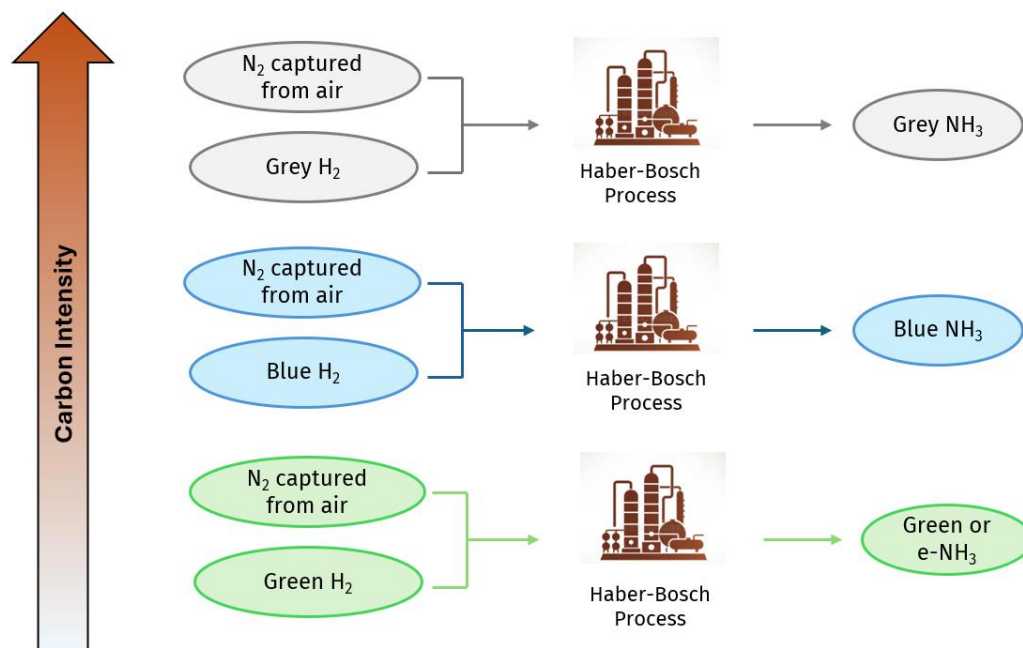


Figure 16: NH₃ production pathways representation

In this work, the focus was placed on ammonia. Therefore, further in-depth analysis has been conducted exclusively on this alternative fuel. However, it is important to note that a wide range of alternative fuels should be considered, as the future marine energy landscape remains uncertain from this perspective. Moreover, the choice of one fuel over another will depend on technical applications and economic considerations.

Ammonia was selected in this study because a long-term decarbonization scenario was considered. Although its TRL in maritime applications is lower compared to MeOH or LNG, ammonia is entirely carbon-free, making it a viable option for meeting more stringent environmental regulations and advancing toward a greener maritime industry.

Furthermore, compared to hydrogen, ammonia enables higher energy storage per unit volume while presenting fewer technical challenges, as it requires a significantly higher storage temperature (-33°C versus -253°C for hydrogen liquefaction). However, ammonia is highly toxic, making rigorous safety assessments of the fuel handling system essential.

2.3. Current and Future Fleet Scenario, Fuel Production, and Port Infrastructures.

Following the identification of technologies that, from a technical standpoint, appear promising for future developments in the naval sector, it is crucial to assess the actual interest they garner. Such

interest can be characterized by global investments aimed at creating a network for production, distribution, and onboard utilization.

Therefore, with a focus on ammonia as an alternative fuel—being the subject of this study—a research effort was conducted to justify the current direction of the global market based on the following three KPIs:

- Ongoing or future projects focused on the production of blue/e-NH₃
- Storage capacity and availability of bunkering infrastructure at major global ports
- Analysis of order books and existing vessels capable of operating with ammonia as fuel
- **Ongoing or future projects focused on the production of blue/e-NH₃**

Regarding the global production capacity of ammonia over the years, the analysis focused specifically on the production of bio/e-NH₃ intended for the maritime market. To this end, data on projects aimed at producing this fuel were extracted using the public Veracity database by DNV [33]. This process resulted in the creation of a dedicated database containing information on maximum capacity at full load and the operational start dates of facilities currently in the design phase, as reported by Veracity. The research was updated to the beginning of 2024, therefore, some variations in the subsequently reported data may be observed.

As evident from [Figure 17](#), the current production of e-NH₃ remains extremely limited. However, a significant increase is expected in the years following 2030, with global annual capacity projected to exceed 160 Mtons/year. Forecasts based on project declarations indicated that, at the beginning of last year, the maximum annual production could reach approximately 200 Mtons/year by 2045.

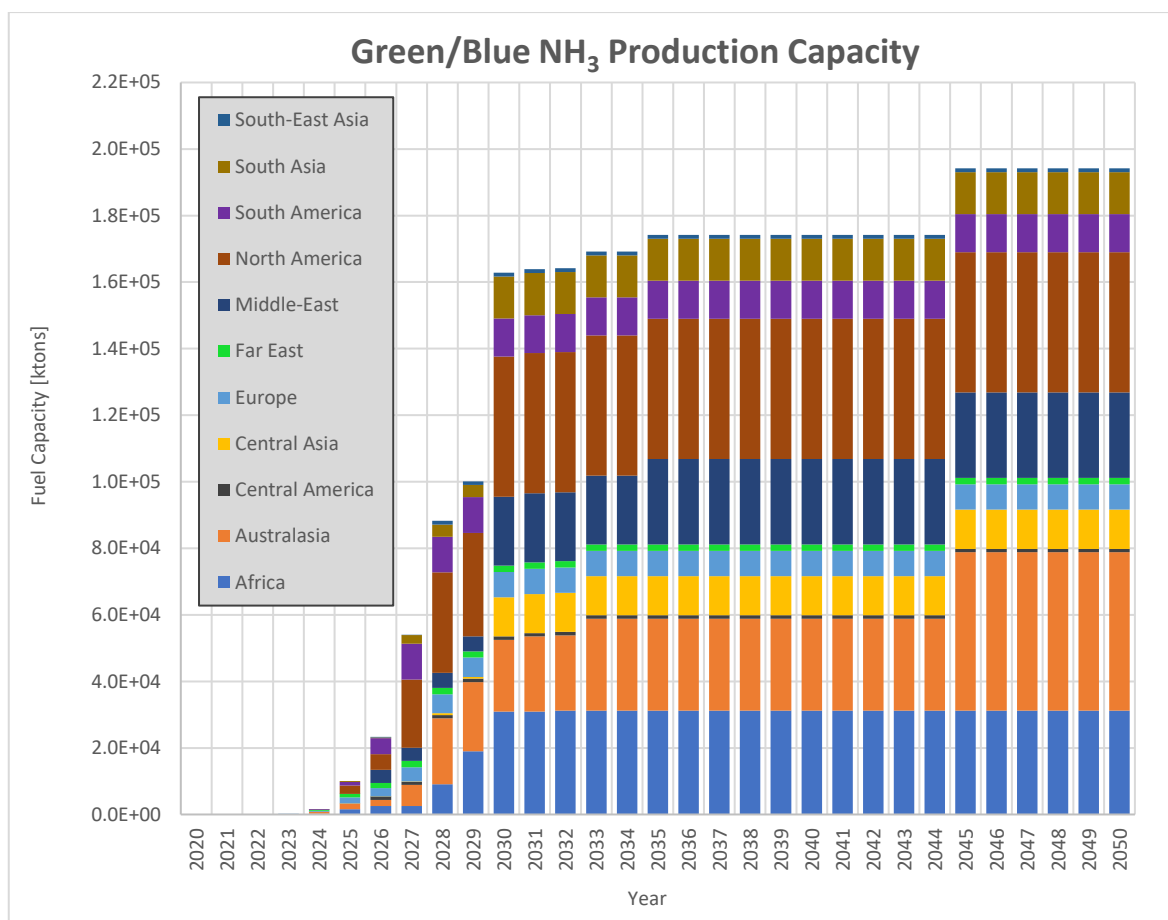


Figure 17: Global absolute annual capacity for blue and e-NH₃ as maritime fuel, updated as of early 2024

In [Figure 18](#), depicting a 2050 scenario, the shares of production capacity for different geographical areas are illustrated. Australasia leads the rankings, contributing 25% of the global low-emissions ammonia supply by 2050. This production is primarily represented by e-NH₃ derived from extensive photovoltaic plants dedicated to the production of e-H₂, particularly in Australia, leveraging the region's high solar potential and the availability of vast inland desert areas. Notable projects in terms of capacity include initiatives such as “Australian Renewable Energy Hub” AREH [39] with a projected maximum e-NH₃ capacity of 9.9 Mtons/year by 2028 [33], and “Western Green Energy Hub” (WGEH) [40], expected to reach a maximum capacity of 20 Mtons/year by 2045 [33] as reported in the Veracity database. However, both projects are classified as “under discussion,” similar to the majority of dedicated projects worldwide. Of the total projects reviewed, 145 were categorized as “under discussion” at the beginning of 2024, compared to only 27 classified as “decided.”

The United States follows with an anticipated 22% share by 2050, aiming to increase low-emission ammonia production capacity through the development of blue-NH₃. This approach relies on CCS technologies to capture CO₂ emissions generated during the steam reforming of natural gas.

Examples include the "Bayton Blue Ammonia" project [41], expected to produce 3.4 Mtons/year of blue ammonia by 2028 [33], and the "Beaumont Blue Ammonia Plant Phase I" [42], projected to deliver 1.1 Mtons/year by 2025, this last classified as "Decided" [33].

In the same scenario, Africa and the Middle East also stand out, projected to achieve shares of 16% and 13%, respectively, due to their high solar potential, similar to Australia. In these regions, e-NH₃ production will take place, ensuring zero-emission outputs.

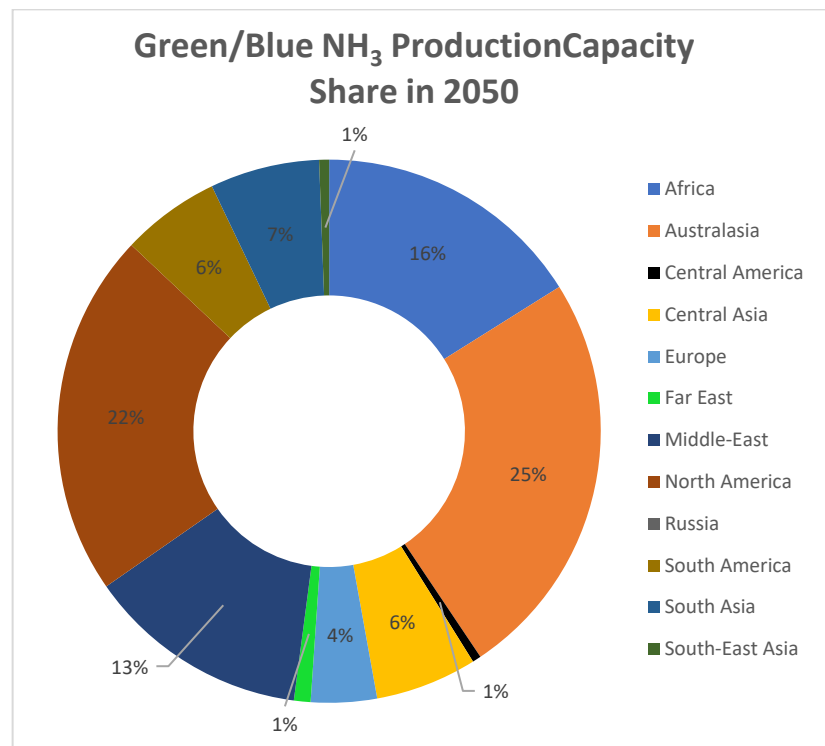


Figure 18: Projected shares of blue and e-NH₃ annual capacity by geographical region in 2050

- **Storage capacity and availability of bunkering infrastructure at major global ports**

This assessment has been conducted based on both port storage capacity and the availability of bunkering infrastructure. From the storage capacity perspective, and leveraging the DNV Veracity Database, the primary assumption made is that all existing ammonia storage facilities can be considered as potential local fuel storage. Currently, ammonia is primarily used as a component in fertilizers and serves agricultural purposes. Consequently, many ports, particularly those near agricultural regions, are already equipped with ammonia storage systems. This assumption has also been supported by the Veracity database, counting of about 220 ports capable of storing ammonia [33].

However, it is acknowledged that if ammonia is to be widely adopted as an alternative marine fuel, the overall storage capacity will need to be significantly expanded. Despite this, only a few port authorities have announced projects to increase their ammonia storage capacity. The majority of these projects, however, remain at an early stage, with most not progressing beyond the feasibility study.

From the perspective of bunkering means, no definitive information are currently available. Generally, three methods can be considered for bunkering operations: truck-to-ship, ship-to-ship, or shore-to-ship. At present, there are no data on operational or planned barges designed for ammonia bunkering through the ship-to-ship process. However, further insights can be derived by referring to the subsequent section on the current fleet scenario, which provides some relevant information on this topic.

The Port of Singapore (MPA), recognized as one of the world's leading bunkering hubs, has demonstrated significant interest in advancing ammonia-related initiatives. In collaboration with other parties, it has submitted a proposal in response to an "Expression of Interest" (EOI) to build, own, and operate a comprehensive low- or zero-carbon ammonia power generation and bunkering solution on Jurong Island, Singapore, as reported in [43].

Additionally, during a technical webinar held on March 1, 2024, the "Global Center for Maritime Decarbonization" (GCMD) highlighted a projected increase in demand for ammonia bunkers in Singapore, with growth anticipated to continue through 2035, as outlined in [Figure 19](#).

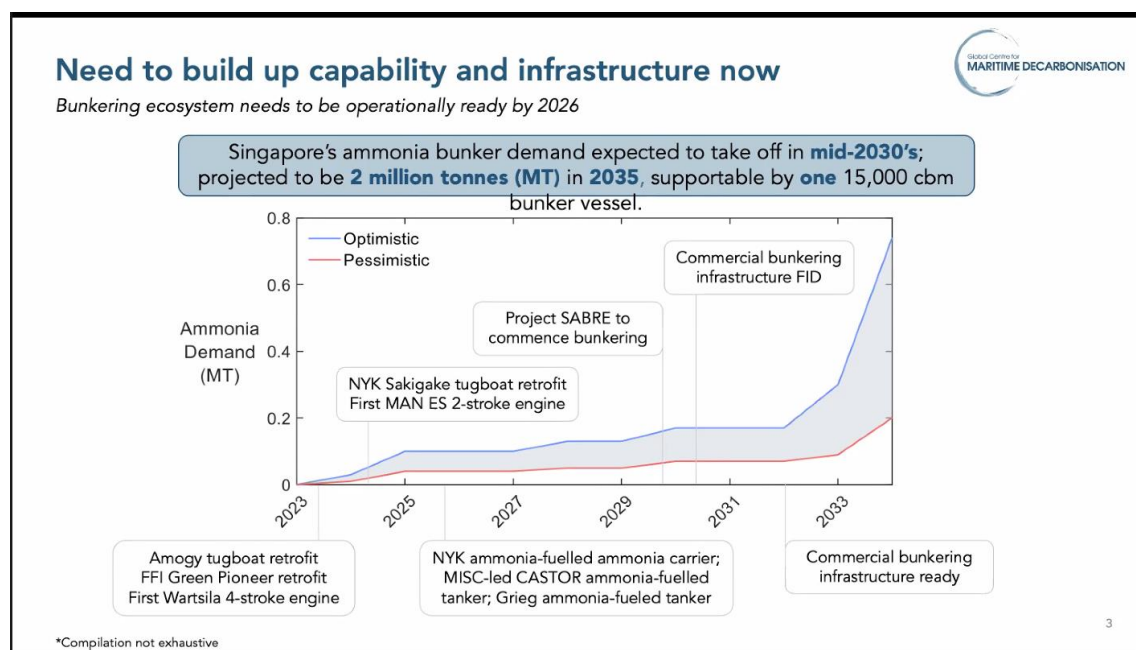


Figure 19: GCMD projection for the ammonia bunkering request in Singapore's port.

In March 2024, the MPA conducted its first ammonia bunkering trial as part of the “*Fortescue Green Pioneer Project*”, utilizing a shore-to-ship approach to assess the feasibility and safety of this operation [44].

- **Analysis of order books and existing vessels capable of operating with ammonia as fuel**

After analysing the situation from the perspective of production, infrastructure, and ammonia bunkering means, it is crucial to provide an initial indication of the potential demand. To gather available public data, ammonia-powered ship order books were identified, focusing on short-term projections using the DNV Veracity database.

Currently, a limited number of ammonia-fuelled ship projects are underway at various stages of development. As shown in *Figure 20*, by 2028, the total number of ships capable of operating on ammonia is projected to reach 33. This figure is based on ongoing projects, therefore, it could reasonably increase significantly with future designs.

All the ships in question are equipped with dual-fuel internal combustion engines (ICE), enabling them to operate using marine diesel oil (MDO) as fuel.

Currently, two ammonia-capable ships are already in operation [33].

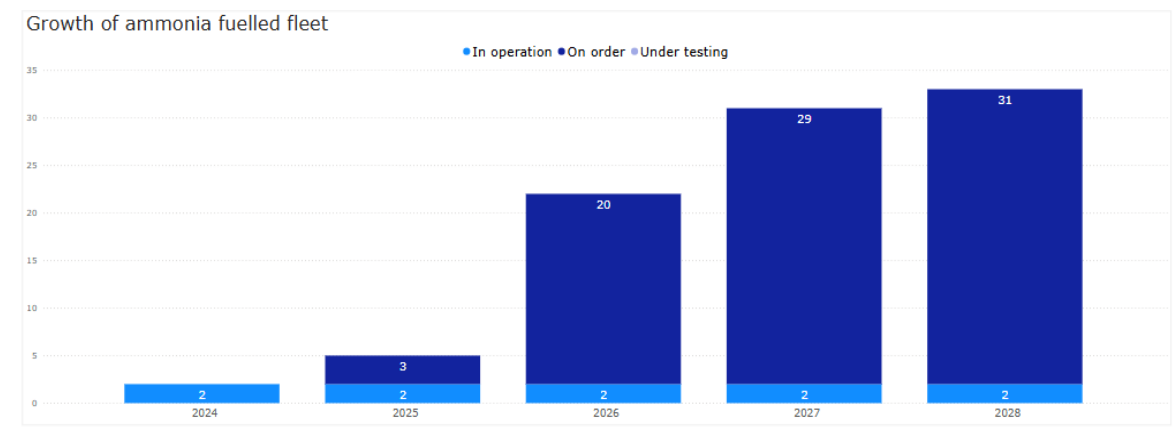


Figure 20: Growth of the ammonia-fuelled fleet based on the order book, updated to 2025

In *Figure 21*, the types of ammonia-powered ships are illustrated. As can be observed, the most suitable candidates appear to be gas tankers and bulk carriers, with 13 projects for each type currently listed in the order books through 2028.



Figure 21: Ammonia-fuelled ships by ship type based on the order book, updated to 2025

Since ammonia is a gas transported in liquid form, ships dedicated to its transport are classified as gas tankers, making them among the primary candidates for adopting ammonia as fuel. This is due to the potential utilization of the cargo as fuel, as is currently the case for LNG carriers. Another implication of this classification is that bunkering vessels, which are also considered gas tankers, could be equipped by ports for ship-to-ship bunkering operations. However, a more detailed study using non-public databases providing finer-grained data would be necessary to draw more reliable conclusions.

On the other hand, bulk carriers also emerge as strong candidates for adopting ammonia as a fuel, likely due to their ability to minimize cargo capacity losses. This type of ship typically has larger unused spaces on the deck compared to, for instance, container ships. Such spaces could accommodate storage tanks without significantly affecting cargo capacity. Naturally, these installations must be compatible with the layout of hatch covers to ensure smooth and safe loading and unloading operations. A potential arrangement for such tanks is illustrated in [Figure 22](#).



Figure 22: Possible storage tank arrangements on bulk carrier vessels

To gain a more comprehensive overview in the medium to long term, it is necessary to expand the evaluations beyond the current order book. According to the latest ammonia demand projections in the ETP2024 report by the International Energy Agency (IEA), the demand for ammonia as a fuel is expected to reach approximately 300 Mtons by 2050 ([Figure 23](#)) [45], more than doubling compared to the scenario projected for 2035. Conversely, the demand for ammonia for primarily agricultural purposes is expected to remain largely unchanged.

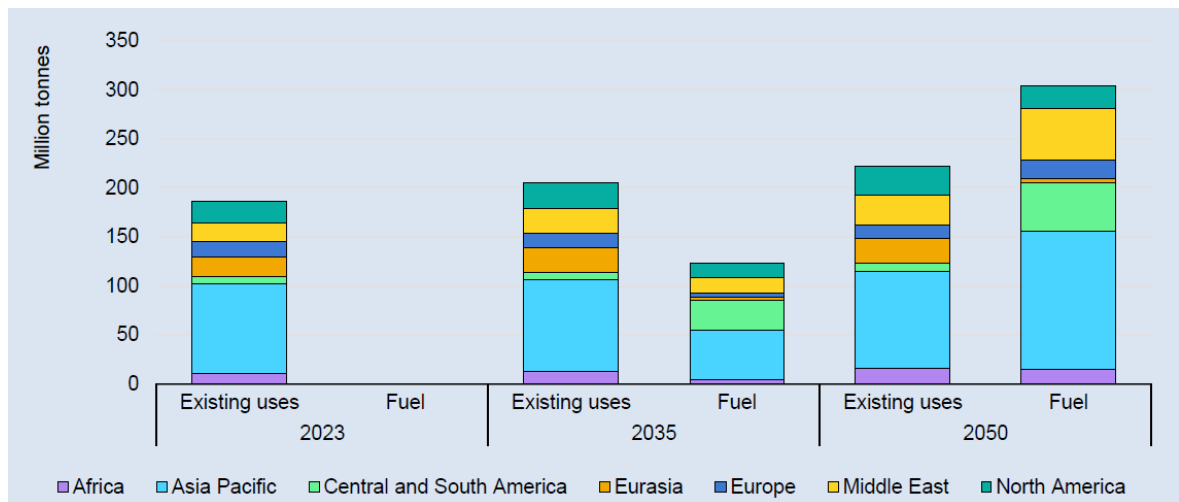


Figure 23: Projected ammonia demand by geographical area and usage type

3. Multicriteria Comparison Analysis.

The purpose of this assessment is to explore the potential of an adapted multi-criteria analysis for identifying the most promising onboard energy system solution. Given the uncertainties related to future market scenarios and the upcoming IMO measures promoting alternative fuels, it is essential to develop a preliminary understanding of the applicability and feasibility of low-carbon solutions for the maritime sector, such as ammonia. This assessment takes into account various technical and operational features, differentiating between ship types.

In this chapter, a marine industry-adapted multi-criteria approach is presented, outlining the necessary arrangements and updates required to enhance the comparison between alternative and conventional solutions. Furthermore, the potential and limitations of this approach have been analysed to integrate the findings into the decision-making process.

Three case studies have been selected, focusing on two of the most relevant ship types from a decarbonization perspective: container vessels and cruise ships. In the evaluation process, cost-related factors emerged as a critical issue due to uncertainties, particularly concerning future fuel prices and carbon levy scenarios. The study concludes that while a multi-criteria approach like this holds significant potential for preliminary assessments, it is not conclusive. A more detailed, case-by-case analysis is necessary, as the outcomes remain strongly dependent on future market developments. Therefore, specific technical requirements cannot be modelled using this approach.

To identify the most promising alternative fuel solution, a multicriteria comparison analysis was selected as the most appropriate preliminary approach. This method provides a structured framework for evaluating various potential alternatives by considering multiple key parameters deemed representative of the specific context of the study. The scope of this approach is extensive, as numerous studies have employed adapted multicriteria methodologies across diverse applications. In this context Priftis et al. [46] applied multi objective optimisation to the design of a single containership, aiming to maximise the capacity and the stowage ratios, as well as to minimize the EEDI and the overall ship resistance. Pesce et al. [47] performed a multi-criteria decision analysis to compare different route alternatives in Venice for cruise ships, considering economic, social and environmental aspects. Aspen et al. [48] applied a stochastic multi-criteria decision analytical approach to reduce emissions on a Norwegian ferry comparing different energy carrier solutions.

Other example of multi-criteria usage for comparison solution are presented in recent literature [49] [50] [51].

Therefore, multicriteria comparison analysis holds significant potential for providing an initial broad screening and offering valuable insights into the most promising solutions to focus on. However, this generality lacks the precision required for case-by-case evaluations, highlighting the need for a more detailed study as following step.

Focusing on the maritime sector, this approach has been adapted for demonstrating the potential of specific technologies under varying operational requirements and boundary conditions, applicable to both new builds and retrofits. In the context of this study, the alternatives within the multi-criteria approach are represented by the available technologies for onboard power generation. These include fuel storage systems, fuel treatment systems, power units, batteries (energy storage), and exhaust aftertreatment systems as key plant components. *Table 10* provides a summary of all the components characterizing each technology as potential alternative.

Fuel Storage	Fuel Treatment	Power Unit	Energy Storage	Exhaust Aftertreatment
LH ₂	-	LT-PEMFC	Li-ion Batteries	-
CH ₂	-	LT-PEMFC	Li-ion Batteries	-
MH	-	LT-PEMFC	Li-ion Batteries	-
LNG	-	SOFC	Li-ion Batteries	-
		DF – CI ICE		SCR
MeOH	-	DF – CI ICE		SCR
MDO	-	CI ICE		SCR
NH ₃	Cracker Reactor	DF – SI ICE		SCR
	-	DF – CI ICE		SCR

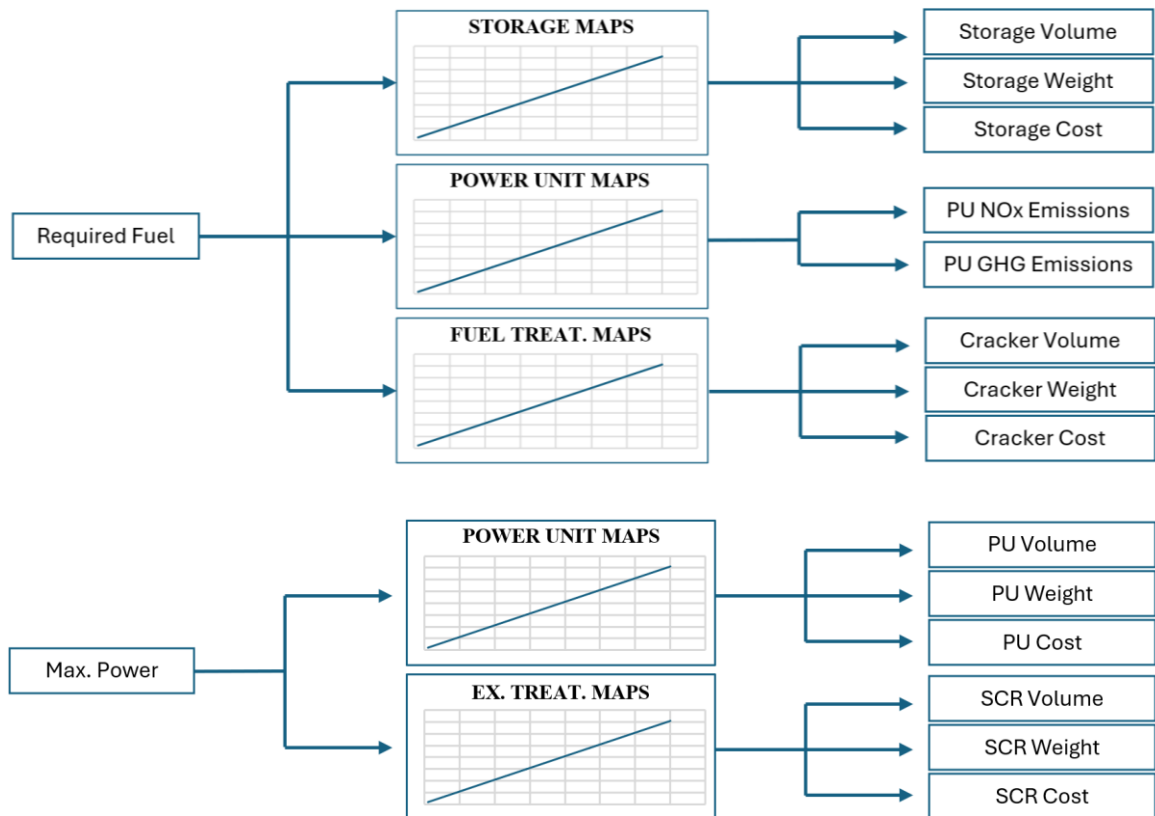
Table 10: Onboard Energy Systems considered in the adapted Multi-Criteria Analysis

Since the multi-criteria comparison can only be conducted based on indicative criteria, key parameters must be identified in alignment with the specific application field. In the context of onboard integration, volume, weight, GHG emissions (CO₂ and CH₄, due to methane leaks), NO_x emissions, costs, and environmental hazards (modelling a potential outboard fuel spillage scenario), have been deemed as indicative criteria upon which the analysis should be based. As shown in *Table 11*, only volume, weight, and costs can be defined for each component of the energy plant. Emissions, however, must be evaluated exclusively based on the power unit, as it constitutes the sole source of emissions. Environmental hazard has been identified as the only criterion that remains entirely independent of the system's components, being solely determined by the chemical properties and physical state of the stored fuel.

Volume, Weight, Cost	GHG, NOx Emissions	Environmental Hazard
Storage System Fuel Treatment Power Unit Batteries Exhausts Aftertreatment	Power Unit	Fuel

Table 11: Key-parameter and related components

Following the above distinction on key-parameters and related items, volume, weight, emissions and costs' absolute values need to be identified for different components. For this purpose, an extensive approach was deemed to be a good pathway to follow. Therefore, a comprehensive market analysis of available data serves as the foundation for developing an extensive database that encompasses both technical and economic parameters for each component. Based on this analysis, the spread data must be appropriately approximated through correlations that establish biunivocal functions between the absolute values of the criteria and a representative variable to be used as input. [Figure 24](#) provides a summary of the input parameters utilized within the maps and their corresponding outputs, depending on the specific component under consideration.



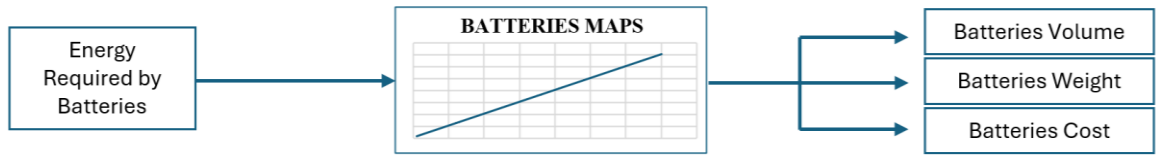


Figure 24: Maps of input variables and related outcomes

The input variables shown in **Figure 24** are defined based on the mission characteristics selected for analysis using the multi-criteria approach. They are derived from the energy requirements necessary for modelling the specific mission under consideration, and representing the main analysis' inputs. Following this approach, the energy inputs are represented by:

- **Maximum Installed power**

It represents the maximum power output achievable by the power unit installed onboard. This value is considered as the input variable for determining the appropriate power unit and the sizing of the SCR system to be installed.

- **Operational Power & Operational Hours**

These variables represent the required power and the mission range to be modelled, respectively. They are interconnected, as together they define the total energy demand, which in turn indicates the amount of fuel required. This fuel quantity serves as a key input variable for determining the storage and fuel treatment systems' volume, weight, and costs, as well as the NO_x and GHG emissions of the power unit. The calculation of the required fuel amount depends on the fuel's chemical properties (LHV, density) and the efficiency of the power unit.

- **Energy Required by batteries**

The energy required by the batteries serves as a key input for calculating their volume, weight, and costs. The inclusion of batteries becomes a critical factor when both LT-PEMFC and SOFC technologies are considered in the analysis. This is because these technologies require a battery system to be integrated for the proper and safe management of load fluctuations.

Once the criteria's absolute values have been defined, a scoring method is used for moving the comparison on the same level. This is need because of the different nature of the criteria. Particularly, a score is calculated and assigned for each key-parameter end for each technology, as represented in (1).

$$S_{ij} = coeff \cdot \frac{(v_{best})_i}{v_{ij}} \cdot R_i \quad (1)$$

Where:

- i = Index relative to the generic key-parameter
- j = Index relative to the generic technology
- S_{ij} = Score obtained by the j^{th} technology for the i^{th} parameter
- $coeff$ = Coefficient introduced in order to represent the score in an appreciable value range
- v_{ij} = Value assumed by the i^{th} parameter for the j^{th} technology
- $(v_{best})_i$ = Value assumed by the i^{th} parameter for the best technology
- $R_i = i^{th}$ Parameter's relevance

Another important variable in this adapted multi-criteria approach is relevance. This is assigned to each key parameter to reflect its relative importance compared to others, effectively serving as a weighting factor. A scale from 1 to 5 has been deemed sufficiently indicative for ranking parameters based on their level of importance, as it ensures a meaningful impact on the final results while maintaining reliable variability. This approach helps reduce potential assignment errors that could arise from using broader ranges.

The relevance assigned to each key parameter is determined by the identification of additional mission inputs, except for cost relevance, which is challenging to standardize as it varies on a case-by-case basis. The other analysis inputs considered relevant to determining the parameter relevance values are described below:

- **Vessel Type**

The type of vessel determines the relevance values assigned to volume and weight. Specifically, some vessels prioritize usable volume for payload as the most critical variable, while others are more constrained by weight due to the high specific weight of their cargo. For the first category of vessels, the potential increase in weight resulting from the implementation of alternative fuel solutions poses no significant issues. However, volume becomes a more critical factor (e.g., passenger ships, container ships). In such cases, alternative energy systems could substantially impact the available space for cargo or passengers, thereby increasing the relevance of volume over weight.

Conversely, for vessels transporting very heavy cargo (e.g., ore carriers), the design approach shifts. In these cases, the primary consideration is the buoyancy required to safely carry the intended cargo load. Here, an increase in the energy system's weight could directly reduce cargo capacity, making

weight the more critical factor. Therefore, a higher weight relevance compared to volume is defined to ensure a proper analysis.

- **Navigation Characteristics**

Navigation characteristics play a crucial role in determining the reference values for emissions. This is because the input for this analysis should be intended as the typical operating area of the vessels. In this context, distinguishing between inland waters, coastal, national, short sea, and deep sea navigation has been considered indicative for both NO_x and GHG emissions. Additionally, the ability to operate within Emission Control Areas (ECAs) specifically influences the relevance of NO_x emissions. The adopted approach establishes a decreasing relevance for emissions as the operational environment shifts from areas closer to sensitive zones to open ocean routes. It is important to note that, unlike NO_x, which are toxic and thus classified as local pollutants, GHGs — primarily composed of CO₂ — have impacts that are felt on a global scale. This decouples GHG emissions from geographical location, as their evaluation should be based on a temporal scale, considering their Global Warming Potential (GWP). Nevertheless, despite this broader perspective, given that a preliminary evaluation is being conducted using a multi-criteria approach, a localized framework has been applied to determine the relevance of GHG emissions.

Once the scores for each key parameter and each technology have been determined using the methodology described above, the adapted multicriteria approach foresees calculating a total score for each technology. This is achieved by summing the individual scores, as outlined in (2).

$$S_{tot j} = \sum_i S_{ij} \quad (2)$$

In this context, the technology with the highest score is identified as the most promising solution, based on the selected input for the analysis.

3.1. Multicriteria Software: Features, Adjustments, and Improvements.

In order to carry out the adapted multi criteria analysis described before, a software called HELM (Helper for Energy Layouts for Maritime applications), developed by the Thermochemical Power Group (TPG - University of Genoa), has been widely adjusted and subsequently used for the analysis in question. This work has been conducted in collaboration with other Ph.D. students. The HELM

software, written in MATLAB, allows to retrace the above explained methodology identifying the most promising solution through the total score evaluation. In [Figure 25](#) the HELM's updated flow chart is shown.

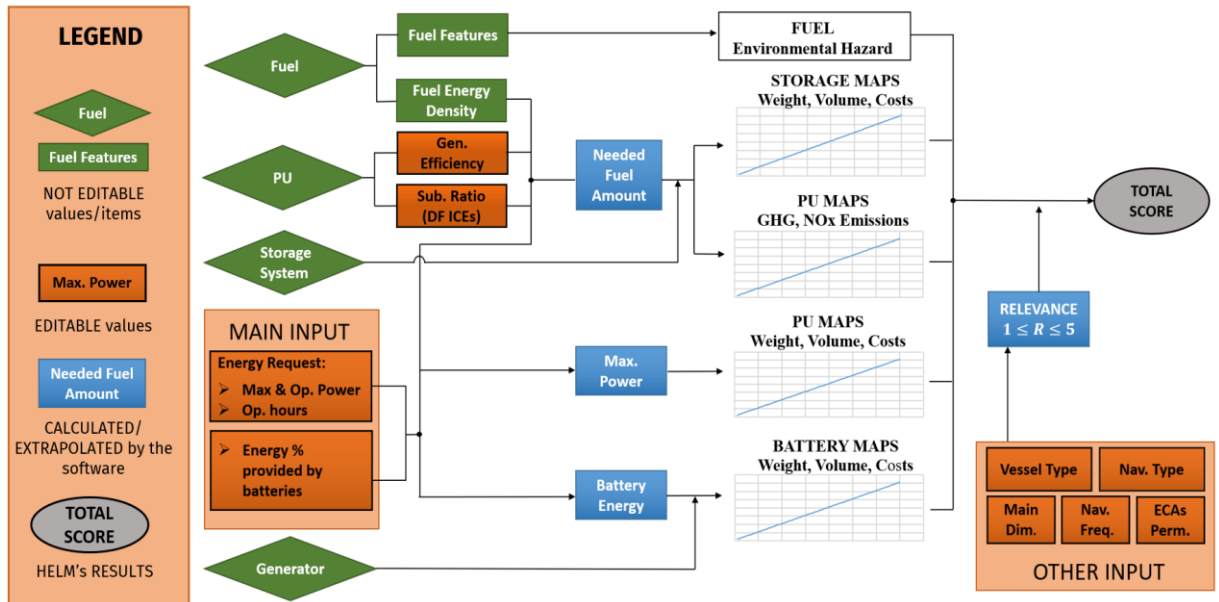


Figure 25: HELM's flow chart

As previously outlined, the main user inputs (energy inputs) are essential for conducting the simulation. Once these inputs are identified, the maximum power and battery energy can be directly used as relative maps' input values. However, the required fuel amount still needs to be calculated. This calculation requires both fuel and power unit characteristics.

Focusing on the power unit, key parameters such as generator efficiency and substitution ratio—representing the heat rate contribution from the alternative and pilot fuels, specifically for dual-fuel internal combustion engines (DF ICEs)—are provided as adjustable values. From this point, the software computes the fuel amount. For each storage technology, depending on the type of fuel, the software can reference the corresponding maps, as illustrated in [Figure 25](#).

Using the previously described scoring method and relevance weighting, the software calculates the total score, completing the multi-criteria analysis. It is important to note that the following additional inputs are required by the software:

- **Main Vessel Dimensions**

This input does not directly contribute to the score evaluation but it provides an indication of the available vessel volume that can be allocated to the energy system, establishing its limits. If a

particular technology, in line with the energy demand, exceeds these constraints, the software will issue a warning regarding the affected technologies.

- **Navigation Frequency**

The navigation frequency allows users to classify the vessel as heavy-duty, medium-duty, or light-duty, which impacts the lifespan of technological components and, consequently, the associated costs due to varying operating hours over the vessel's lifetime. This input is essential because the software is designed to simulate a wide range of vessel types, including small leisure vessels. As a result, it is necessary to account for different average operating times.

As shown in [Figure 26](#), the software user interface is organized into two distinct sections. The first section allows the user to identify the main inputs and adjustments, making the software highly flexible for accurately simulating a wide range of missions. The second section presents the results, displaying both the scores and key output values. Additionally, the output visualization can be further expanded by exporting an Excel table that also includes the initial assumptions.

Barge

Pax Ferry

Pax & Car Ferry

Cruise Ship

RoRo Ship

Container Ship

Hull Number

1

Length [m]

0

Hull Beam [m]

0

Upper Beam [m]

0

Hull Height [m]

0

Upper Height [m]

0

Installed Power [kW]

0

Operational Power [kW]

0

Operational hours

24

Frequency

Medium

Low

Heavy

Type

Coastal

National

Short

Deep

ECAs

50 - 100 %

Annual Mission Number

0

Carbon Tax

i

EU EMS, CO2 Tax [USD/ tonsCO2]

0

Fuel Price [USD/tons]

MDO

800

LNG

1014

H2

6090

MeOH

350

NH3

480

Energy Systems Characteristics

	i	i	i	i	i	i	i	i
Power Unit	PEMFC MH	PEMFC LH2	PEMFC CH2	SOFC LNG	ICE MDO MeOH	ICE MDO LNG	ICE MDO	ICE NH3
Main Fuel	--	--	--	--	amb	amb	amb	amb
Second Fuel	--	--	--	--	amb	amb	amb	amb
Pressure [barG]	10 - 30	amb - 10	350	amb - 10	amb	amb	amb	amb
Substitution [%]	--	--	--	--	95	95	--	--
Energy System Efficiency [%]	50	40	50	53	35	35	35	35
Battery Type	Store	Store	Store	Store	Store	Store	Store	Store
Battery Energy Contribute [%]	15	15	15	15	0	0	0	0
CO2 Capture Rate [%]					0	0	0	

Relevance

Costs Rel	Volume Rel	Weight Rel	NOx Rel	GHG Rel	Envir Haz Rel
1	1	1	1	1	1

Results

		Main Results		Detailed Results			
	Power Tech Avail	Tot Weight [tons]	Tot Volume [m3]	Tot Cost [kUSD]	GHG [tons CO2eq]	NOx [kg]	Noise [dB]
PEMFC MH	+	0.00	0.00	0.00	0.00	0.00	0.00
PEMFC LH2	+	0.00	0.00	0.00	0.00	0.00	0.00
PEMFC CH2	+	0.00	0.00	0.00	0.00	0.00	0.00
SOFC LNG	+	0.00	0.00	0.00	0.00	0.00	0.00
ICE MDO MeOH	+	0.00	0.00	0.00	0.00	0.00	0.00
ICE MDO LNG	+	0.00	0.00	0.00	0.00	0.00	0.00
ICE MDO	+	0.00	0.00	0.00	0.00	0.00	0.00
ICE NH3	+	0.00	0.00	0.00	0.00	0.00	0.00
ICE MDO NH3	+	0.00	0.00	0.00	0.00	0.00	0.00

Figure 26: User interface displaying input requirements and outcomes

3.1.1. User Input and relevance attribution adjustment

The widest HELM's adjustment regards the introduction of a broad user input selection. This modification have been carried out for conducting a more detailed comparison analysis and to give the software more reliability and flexibility. Older HELM's versions allow to identify as main input only the maximum power and the operational hours. The generator efficiencies were editable, while all relevance appeared as user input. This latter approach allowed for a wide margin of inaccuracy in defining relevance, as it relied solely on the user's background. Therefore, it was deemed necessary to adopt a more scientific approach for relevance identification, integrating it with the case study definition and automatically assigning a predefined value. A schematic representation of the current user-configurable inputs and editable values is provided in [Table 12](#).

User Inputs	Further Editable Values
• Vessel Type • Vessel Main Dimensions • Installed Power • Operational Power • Operational Hours • Navigation Frequency • Navigation Type • ECAs Navigation • Cost Relevance	• Annual Missions Number • Carbon Levy Cost • Fuel Prices • CH₂ Storage Pressure (200, 250, 350, 700 bar) • PU efficiencies • Battery type (Storage/Power, based on required C-rate) • Substitution Rate • Battery Energy Contribution

Table 12: User input and editable values summary

3.1.2. Maps updating and implementation of new technology

Several updates have been introduced to the technology maps within the software to achieve the previously stated objectives. This intervention enables the inclusion of the most recent products from various manufacturers, ensuring that the software remains up to date and supports more reliable simulations. In terms of new technologies, the DF-CI ICE fuelled by NH₃ and MDO/MGO as pilot, has been introduced in the multi-criteria approach, since it represents the primary ammonia technology on which the market is focusing. This update was essential both to align HELM with global trends and to enhance the accuracy of simulations for this study. In this regard, major marine engine manufacturers, specifically Wärtsilä and WinGD have been considered to gather technical data on available products. Wärtsilä produces a 4-ST DF-ICE available in various cylinder configurations, covering a power range from 1,890 kW to 3,105 kW [52]. These features make this

product more suitable for small vessel applications. On the other hand, WinGD offers three 2-ST DF-ICE [53], designed to meet the higher power requirements of larger cargo vessels.

Although the available product number is still limited, hindering the building of solid correlations, the identified maps in terms of volume and weight are shown in [Figure 27](#) and [Figure 28](#), respectively. For both key parameters, a linear correlation effectively described the range of values represented by existing technologies.

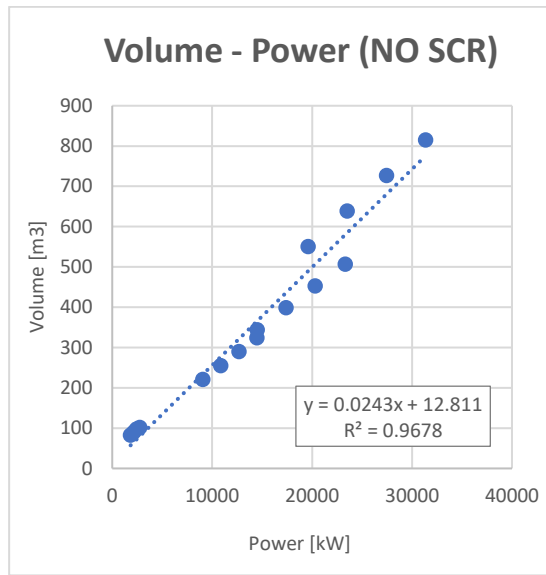


Figure 27: Volume Map of DF-CI ICE fuelled by NH₃ and MDO/MGO

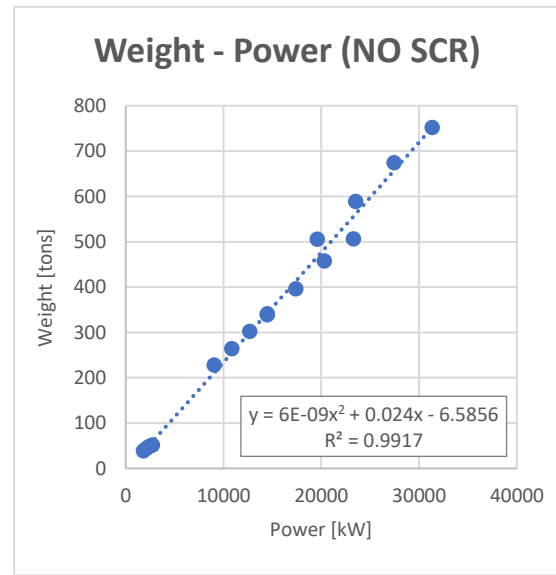


Figure 28: Weight Map of DF-CI ICE fuelled by NH₃ and MDO/MGO

This approach allowed for the scaling of the indicated key parameters as a power function, extending the evaluation to sizes that do not exist yet. However, it is important to note that some uncertainties may arise when deviating from the available power ranges, which could reduce the accuracy of the assessment. For this reason, identifying a correlation that performs consistently even for out-of-range sizes is crucial in the evaluation. In this case, a linear correlation both satisfies the compliance with this requirement and fits the known data appropriately.

3.1.3. Introduction and Adjustments of Key Parameters.

Key parameters are fundamental to the multi-criteria approach and must be defined with precision, as they represent the criteria upon which this analysis is based. Consequently, certain adjustments are necessary to obtain a more realistic scenario.

Regarding costs, additional factors have been considered to accurately model technology expenses throughout the entire lifespan of the ship. Specifically, fuel prices, editable carbon tax values, and the capital expenditure (CAPEX) for replacing technology components have been incorporated into both the initial CAPEX and operating expenses (OPEX). This enables a comprehensive estimation of the total cost of the ship over its operational life, taking into account the average mission requirements provided by the user, which are extended over the same time period.

The emissions score has been refined by introducing greenhouse gas (GHG) components to account for all factors contributing to global warming. In this context, due to its high global warming potential (GWP20), methane (CH₄) has been included to address the issue of methane leakage from dual-fuel internal combustion engines (DF ICE) powered by LNG. To facilitate this integration, methane has been expressed in terms of its CO₂ equivalent, as outlined in (3).

$$(GHG\ Em.)_j = (CO_2\ Em.)_j \cdot GWP20_{CO_2} + (CH_4\ Em.)_j \cdot GWP20_{CH_4} \quad (3)$$

The "Environmental Hazard" has been introduced as an additional parameter. The purpose of this criterion is to assess the environmental impact of different fuels, specifically in the event of an outboard spill. It is measured using four indicators that assess the potential damage each fuel may cause. These are divided into two categories related to atmospheric effects, and two related to water contamination.

For the atmospheric effects, Global Warming Potential (GWP20), which measures CO₂ equivalent emissions over a 20-year period, and the gas' atmospheric lifetime are considered. For water contamination, LD50 and fuel solubility are taken into account. LD50 refers to the dose of a substance that causes the death of 50% of a test group exposed for 4 hours, while solubility in water refers to a substance's ability to dissolve in water, enabling its concentration to decrease to below harmful thresholds over time.

In the context of the Environmental Hazard parameter, a distinction is made between different fuels. Gaseous fuels under ambient conditions primarily impact the atmospheric indicators (GWP20 and gas lifetime), whereas liquid fuels predominantly influence the water-related indicators (LD50 and solubility). The only exception is anhydrous ammonia (NH₃), which, due to its high toxicity and solubility in water, is considered in both atmospheric and water contamination effects.

3.1.4. Scoring Method Adjustment.

The scoring method has been refined by assigning specific scores to each technology and parameter, as outlined in (1). This enhancement allows for a more granular evaluation, moving beyond the

discretized score allocation used in the original approach. Specifically, the previous method involved determining an X value for each performance parameter, as shown in (4).

$$X_{ij} = \frac{v_{ij}}{(v_{best})_i} \quad (4)$$

Based on X_{ij} , different ranges have been identified as significant for score attribution, as represented in [Table 13](#).

X_{ij} Range	S_{ij}
$1.1 < X_{ij}$	10
$1.1 \leq X_{ij} < 1.3$	9
$1.3 \leq X_{ij} < 1.6$	8
$1.6 \leq X_{ij} < 2$	7
$2 \leq X_{ij} < 3$	6
$3 \leq X_{ij} < 4$	5
$4 \leq X_{ij} < 6$	4
$6 \leq X_{ij} < 8$	3
$8 \leq X_{ij} < 10$	2
$X_{ij} \geq 10$	1

[Table 13: Obsolete scoring method](#)

Using this approach, each score must be multiplied by the related relevance assigned by the user.

By adopting a more organic scoring method, it was possible to streamline the code by eliminating multiple *if* cycles, while also achieving a higher level of detail in the scoring process.

3.2. Indicative Case Studies Identification.

To conduct a preliminary comparative analysis of different technologies suitable for onboard implementation, a case study selection was necessary. To maintain a broad perspective, two ship types were chosen, reflecting distinct operational characteristics: containerships, and cruise ships. This selection aimed to assess the feasibility and potential of ammonia as an alternative fuel across various vessel types of interest.

Containerships were selected due to their significant contribution to global CO₂ emissions, as highlighted in the IMO Fourth GHG Report [54] and illustrated in [Figure 29](#). Given their substantial environmental impact, these vessel types are critical targets for emission reduction efforts within the maritime sector.

A second case study, a cruise ship, was included to explore a completely different vessel category. The adoption of ammonia as a fuel for passenger vessels presents mainly safety challenges, making this case particularly relevant for assessing the feasibility of ammonia-fuelled propulsion in a highly regulated environment.

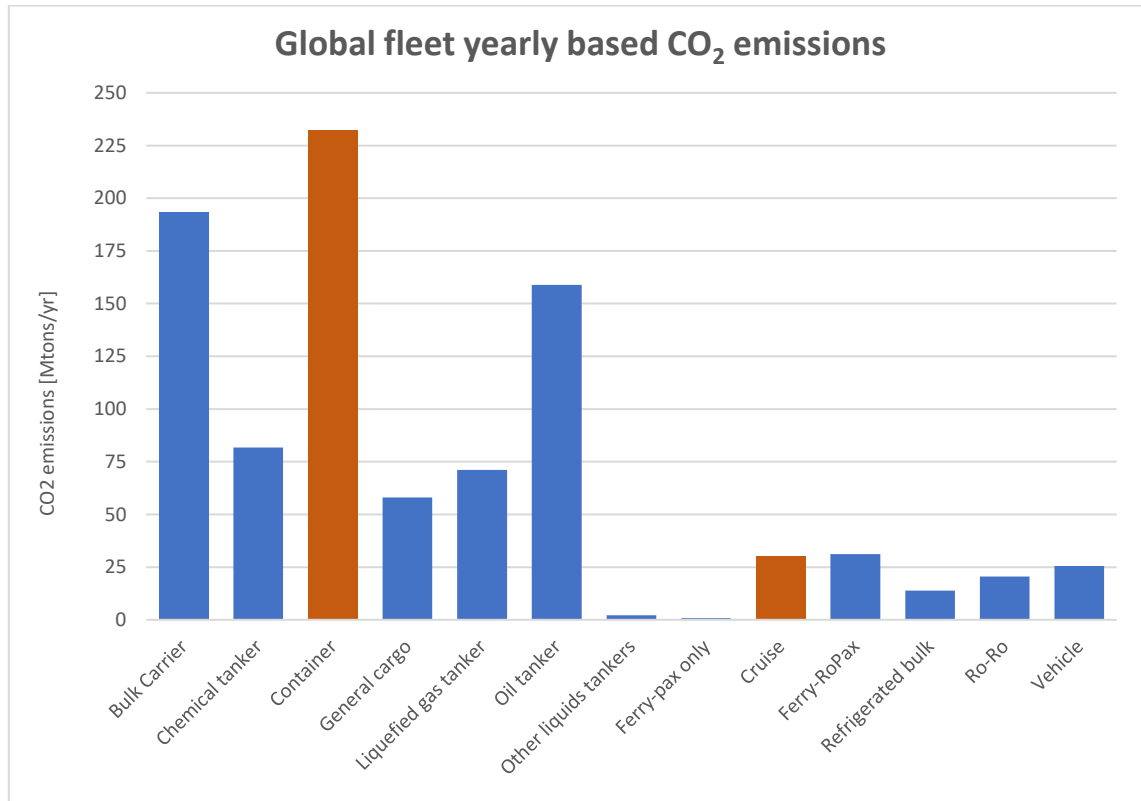


Figure 29: CO₂ annual emissions from the international fleet, categorized by ship type

To better define the case study, a selection based on dimensions and average operational characteristics must be conducted. The IMO Fourth GHG Study [54] provides data on various size categories, specifying the total annual CO₂ emissions and the average size in terms of Deadweight Tonnage (DWT) for each category, as reported in [Table 14](#) for the targets.

By considering the number of vessels classified within these size categories, the indicative case studies for containerships and cruise ships have been selected based on the annual CO₂ emissions per ton of DWT, highlighted in [Table 14](#).

This approach ensures that specific emissions per cargo unit are taken into account while also considering the number of vessels within each size category. As a result, it helps identify the containership and cruise ship subgroups that may require greater attention in decarbonization efforts.

Therefore, small container vessels within the 1,000–1,999 TEU size category, which recorded the highest annual CO₂ emissions per ton of DWT (1,470 tons CO₂ per tons DWT per year), have been selected as interesting case study.

A further comparison was then conducted by extending the simulation to large container vessels, in order to highlight the comparison results across different operational requirements, characterizing different sizes. For this purpose an ocean-going container ship within the 14,500–19,999 TEU size category was simulated.

Ship Type	Size Bin	N. of ship	Averaged DWT [tons]	Total CO ₂ Emissions [Mtons/yr]	Emitted CO ₂ per unit DWT [tons _{CO2} /tons/yr]
Containership	0-999 (TEU)	861	8,438	10	1,185
	1,000-1,999 (TEU)	1,271	19,051	28	1,470
	2,000-2,999 (TEU)	668	34,894	20.9	599
	3,000 – 4,999 (TEU)	815	52,372	39.4	752
	5,000 – 7,999 (TEU)	561	74,661	40.7	545
	8,000 – 11,999 (TEU)	623	110,782	57.9	523
	12,000 – 14,499 (TEU)	227	149,023	22	148
	14,500 -19,999 (TEU)	101	179,871	9.7	54
	≥ 20,000 (TEU)	44	195,615	3.5	18
Cruise	0 – 1,999 (GT)	126	3,115	1.7	546
	2,000 – 9,999 (GT)	110	867	1.1	1,269
	10,000 – 59,999 (GT)	105	4,018	4.2	1,045
	60,000 – 99,999 (GT)	98	8,249	11.4	1,382
	100,000 – 149,999 (GT)	61	10,935	8.6	786
	≥ 150,000 (GT)	21	13,499	2.9	215

Table 14: Size categories of containerships and cruise ships with their main average characteristics in terms of dimensions and annual emissions.

Regarding cruise ships, when assessing their economic potential, DWT is not the most suitable metric. Instead, passenger vessels such as cruise ships and ferries are better represented by Gross Tonnage (GT), which reflects the space allocated to guests and serves as a more reliable indicator of earnings potential. However, due to the lack of data on average GT, CO₂ emissions per unit of DWT were used to select the most indicative case study. This analysis identified the 60,000–99,999 GT size category, which records emissions of 1,382 tons CO₂ per ton of DWT per year, as the most problematic in terms of emissions.

To establish a link between DWT and the most representative GT, a mapping of ships within the identified size category was conducted. As shown in [Figure 30](#), there is no direct correlation between DWT and GT for cruise ships. In this context, a linear correlation can be used as an approximated

descriptor between previous metrics indicating an average of 79,500 GT corresponding to 8,249 DWT.

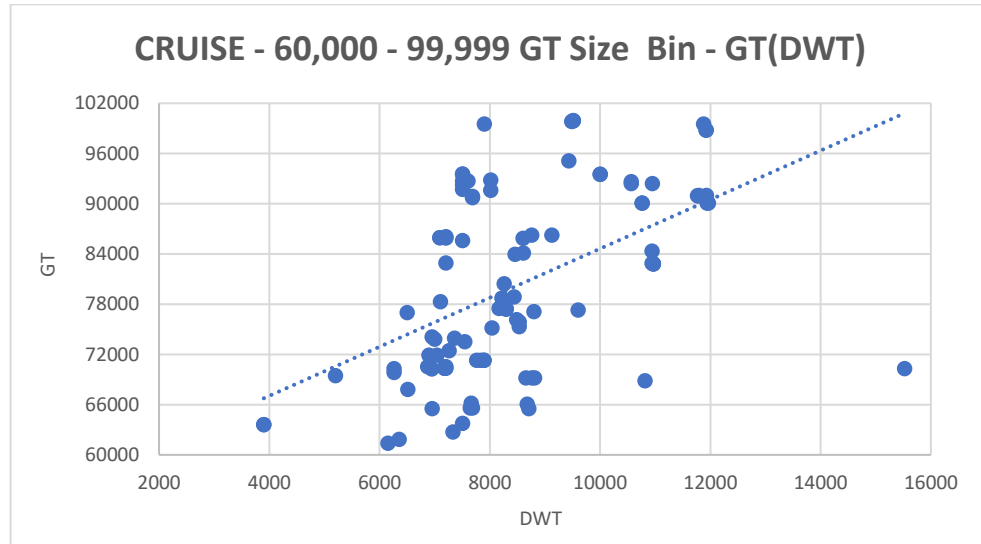


Figure 30: Relation between DWT and GT for cruise ship within the 60,000 - 99,999 GT size bin

Once the ship type was selected, the main data gathering was conducted based on further available information from the IMO Fourth GHG Report [54], particularly regarding average installed power, average days at sea and average design speed.

Furthermore, an indicative sample voyage needed to be identified to estimate the mission's energy requirements. For the small containership case study, given its reduced dimensions, a non-oceanic sample voyage was considered. This choice was made because small container vessels primarily operate on short routes, which require greater attention to emissions due to their proximity to more environmentally sensitive areas. In this context, a typical Mediterranean route connecting Marseille to Algeiras (Gibraltar) was selected, covering a distance of approximately 700 nautical miles. Based on the average design speed characteristic of this vessel size, a travel duration of approximately 37 hours was calculated. This duration was subsequently adopted for the simulation, assuming that the ship can refuel once in port, with an additional range provided by supplementary MDO storage.

Conversely, the large container vessel was simulated using an ocean-going sample voyage connecting Los Angeles to Shanghai. This route was chosen as it represents the busiest container trade route in the world [55], making it one of the primary candidates for green corridor development. Consequently, the distance along this route was estimated to be approximately 5,700 nautical miles, resulting in a required range of 283 hours.

Regarding cruise ships, it was considered that, for tourism-related reasons, this type of vessel must be able to navigate in protected areas as well as Emission Control Areas (ECAs), which have specific emission requirements. Unlike containerships, which follow strict route planning and are classified as liner vessels, cruise ships operate under more flexible schedules during their lifespan, undertaking various cruise itineraries across different regions of the world. These itineraries involve diverse operational conditions, including varying speed requirements. For this reason, a specific sample route was not selected. Instead, due to the frequent port calls, a maximum range of 72 hours using alternative fuel was directly assumed.

The data for both the container vessels and the cruise ship are summarized in [Table 15](#), [Table 16](#) and [Table 17](#), respectively.

SMALL CONTAINERSHIP		LARGE CONTAINERSHIP		CRUISE SHIP	
Installed Power	12,080 kW	Installed Power	60,200 kW	Installed Power	51,520 kW
Operational Power	9,700 kW	Operational Power	46,160 kW	Operational Power	25,000 kW
Alternative fuel Range	37 h	Alternative fuel Range	283 h	Alternative fuel Range	72 h
Expected mission number	136 per year	Expected mission number	21 per year	Expected mission number	85 per year

Table 15: Small containership case study main data

Table 16: Large containership case study main data

Table 17: Cruise ship case study main data

From a cost perspective, which represents a key consideration, the selection of fuel prices and carbon levies—both of which drive a ship's annual operational costs—must be carefully determined.

As an initial approach, grey methanol (MeOH) and grey ammonia (NH₃) were considered. This choice was made due to the high uncertainty surrounding the future prices of MeOH and NH₃ when produced through more sustainable processes. Therefore, more stable and predictable values were preferred.

In this context, it is important to highlight that a Tank-to-Wake (TtW) assessment can be conducted using HELM. However, for a more comprehensive sustainability analysis, an integrated approach considering a Well-to-Wake (WtW) emissions perspective should also be performed.

Evaluation approaches and related references for the identification of both fuel costs and carbon levy are reported in [Table 18](#).

Fuel/Substance	Price	Approach	Considered Period	Reference
MDO	820 \$/mt	Global Averaged Bunker Price	Apr. 2024 – Feb. 2025	[56]
LNG	1,014 \$/mt	Averaged two-region value	n.a.	[57]
MeOH (Gray)	352 \$/mt	Global 4 ports Averaged Bunker Price	Apr. 2024 – Feb. 2025	[56]
NH ₃ (Gray)	480 \$/mt	Global Averaged Price (Not at bunker)	Nov. 2024 – Feb. 2025	[58]
CO ₂ (Carbon Levy)	80 \$/mt	EU ETS	Current Value (Feb 2025)	[59]

Table 18: Considered fuel prices and carbon levy with main assumptions

3.3. Analysis of Simulation Results.

Using previous data, simulations have been carried out for both the small and large container vessel, as well as for the cruise ship. Since all applications require a high energy demand for propulsion, fuel cells have not been considered practicable, as no commercial solutions capable of delivering the required power are available on the market. Similarly, no modular systems meeting these requirements have been tested yet.

Despite this, the software calculated the scores achieved by both LT-PEMFC and SOFC. In particular, LT-PEMFC, when coupled with LH₂, CH₂, and MH as hydrogen storage solutions, resulted in very low scores. This is primarily due to the low energy densities of hydrogen and the bulky and heavy storage systems required. Additionally, fuel cell technologies represent a disadvantage not only from this perspective but also in terms of cost.

Dual-fuel spark ignition internal combustion engines (DF-SI ICE) powered by ammonia and hydrogen—where hydrogen is derived from ammonia via an onboard cracking unit—were not considered due to the lack of detailed information on real-scale products. In fact, studies on ammonia DF-ICE for maritime applications remain limited, with only small-scale engine experiments simulating different substitution ratio (SR) [60] [61]. Additionally, ammonia cracking units are currently developed mainly for terrestrial applications, with only a few companies proposing initial solutions for marine use [62] [38]. Therefore, due to the low technology readiness level (TRL) of this energy system and the uncertainties surrounding its actual performance, it was not directly included in the comparison.

Current market strategies for ammonia-fuelled engines are primarily focused on dual-fuel compression ignition engines (DF-CI ICE) using marine diesel oil (MDO) or marine gas oil (MGO) as pilot fuels. This approach reduces technical and operational challenges while offering greater flexibility in fuel switching.

Therefore, the analysis focused on DF-ICE fuelled by alternative fuels (MeOH, LNG, NH₃) and conventional DF-ICE fuelled by MDO/MGO.

Starting from the large container vessels, [Figure 31](#) presents the score results obtained for this case study. Subsequently, [Figure 32](#) and [Figure 33](#) represent the different item shares composing the most impactful key parameters, represented by volume and cost, for this case study.

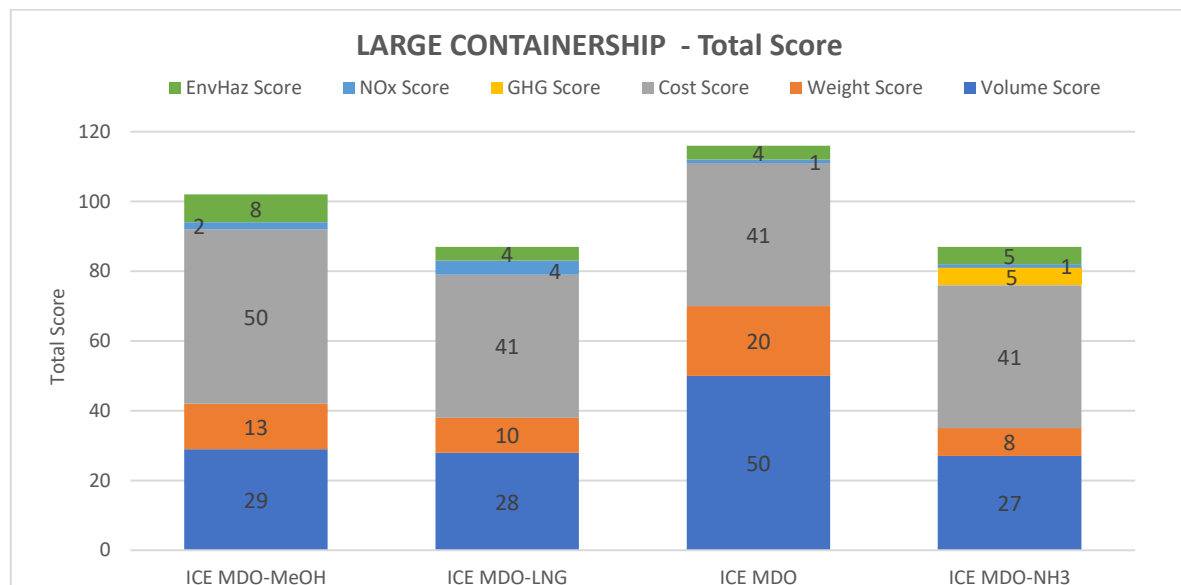
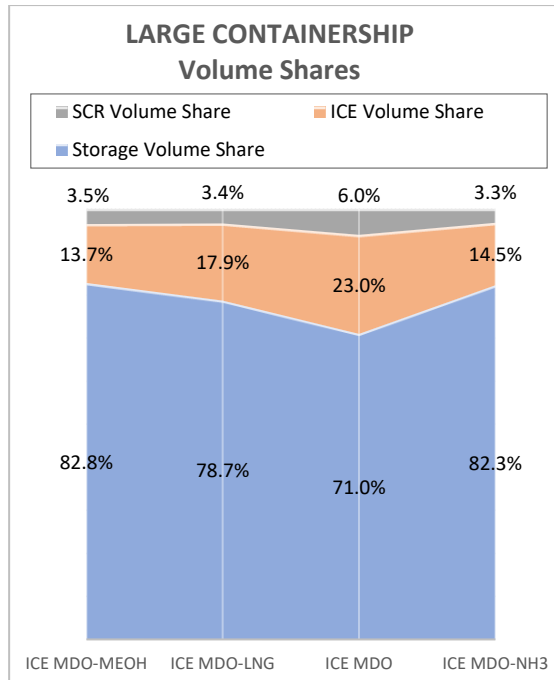
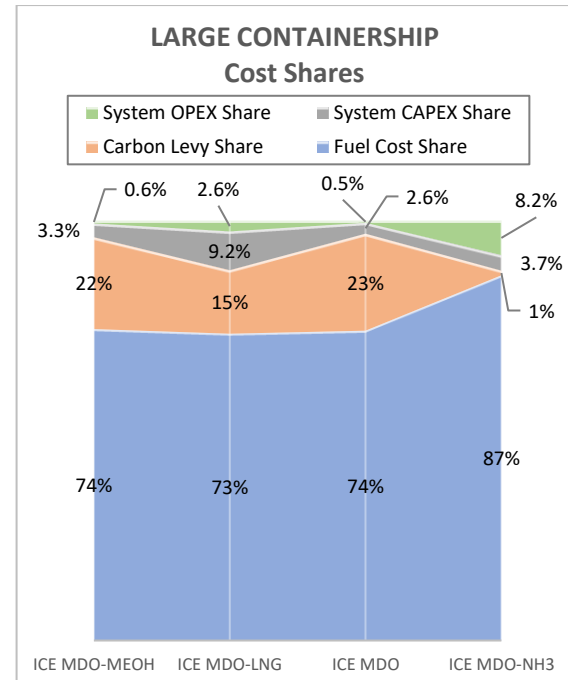


Figure 31: Score results from the multi-criteria analysis applied to the large container vessel case study



	Total Volume
DF-ICE MDO-MeOH	9,588 m ³
DF-ICE MDO-LNG	9,922 m ³
ICE MDO	5,600 m ³
DF-ICE MDO-NH3	10,354 m ³

Figure 32: Different volume item shares of the total volume for all technologies.



	Total Yearly Cost
DF-ICE MDO-MeOH	51.19 M\$/yr
DF-ICE MDO-LNG	63.02 M\$/yr
ICE MDO	61.82 M\$/yr
DF-ICE MDO-NH3	62.84 M\$/yr

Figure 33: Different cost item shares of the total volume for all technologies.

As shown in [Figure 31](#), the conventional ICE fuelled by MDO represents the most suitable solution, performing well from various key-parameter perspectives, especially from a volume standpoint. In this context, as highlighted in [Figure 32](#), which illustrates the volume share of the main system components (storage system, power unit, and SCR for NO_x reduction), the storage system represents the largest portion. Consequently, given the high importance of volume, the storage system becomes highly sensitive to this key parameter. Since MDO is liquid at ambient conditions, it can be stored within structural tanks without requiring particularly bulky, heavy, or expensive storage systems. Furthermore, MDO has a high volumetric energy density, allowing for less fuel storage while providing the same amount of energy compared to other alternative fuels. These two factors make MDO the best solution from a volume perspective, achieving the highest score.

The same considerations apply to weight, with MDO once again emerging as the best solution from this perspective. In this case, the weight relevance allocated to this type of ship is lower than that of volume; as a result, a smaller absolute difference was found among the scores of all technologies.

Considering the other impactful key parameter, represented by costs, a more balanced scenario has emerged across all technologies. Since a container ship is designed to generate revenue through its shipping activity, special attention must be given to both direct and indirect costs—such as potential cargo loss, which was previously modelled through volume relevance. Therefore, the cost relevance was set to 5 in the analysis. The obtained results, shown in [Figure 31](#), indicate that, unlike volume, costs are not primarily driven by system components. In fact, CAPEX and OPEX represent only a small share of the total cost across all technologies, as shown in [Figure 33](#). Instead, the most significant cost factors are fuel price and the carbon levy.

Fuel cost is directly linked to the related price and the amount of fuel required to meet energy demands, reflecting its energy density characteristics. Meanwhile, the carbon levy is tied to the chemical composition of the fuel, as it represents a cost associated with CO₂ emissions. Given the strong influence of fuel price and carbon levy on the cost parameter, this analysis highlights how uncertainties in future fuel and CO₂ prices—largely driven by socio-economic factors—can drastically reshape projections and, consequently, the real market.

As a simulation result, in the perspective outlined in [Table 18](#), MeOH emerges as the most promising solution from a cost perspective. The main reason for this is its price (\$352/mt), which compensates for the higher fuel amount and the carbon levy, set at \$80/mt. From this perspective, ammonia minimizes the cost related to the carbon levy, as its only contribution comes from the pilot fuel. However, due to the higher NH₃ price, it does not emerge as the most cost-effective solution.

In terms of emissions, this containership case study presents low relevance (1) due to the specific navigation characteristics. From a GHG emissions perspective, ammonia is the best solution; however, this advantage is not enough to make ammonia a leading alternative when the previously discussed cost boundary conditions are considered.

The second case study, the small container ship, was identified as the most representative size for enhanced decarbonization due to its fleet emissions. The total score results are illustrated in [Figure 34](#), while [Figure 35](#) and [Figure 36](#) present the volume and cost shares, following the same approach previously adopted for the large container vessel.

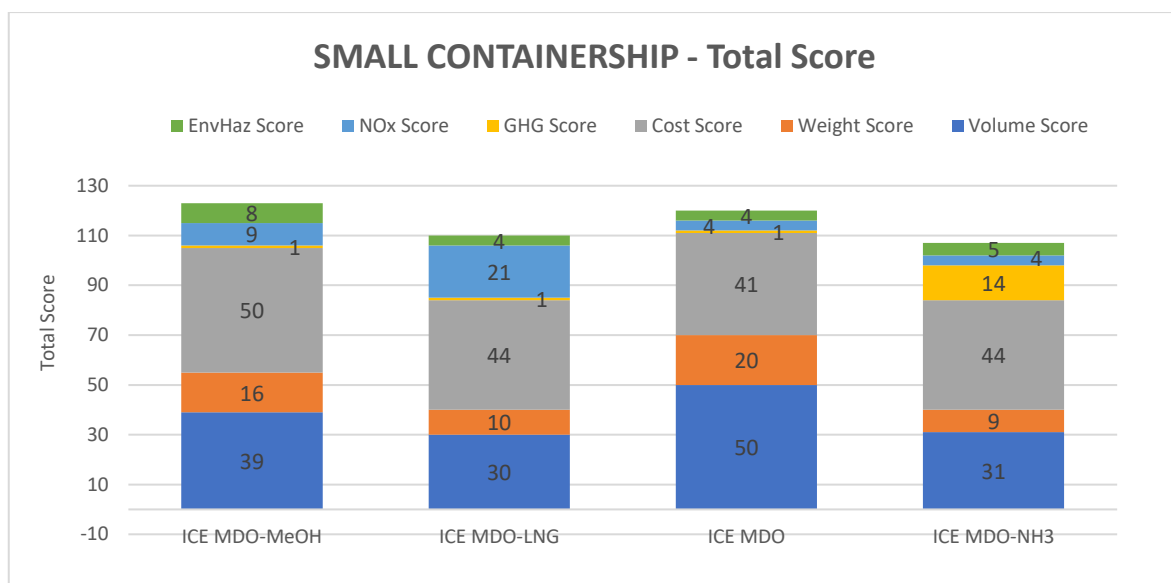
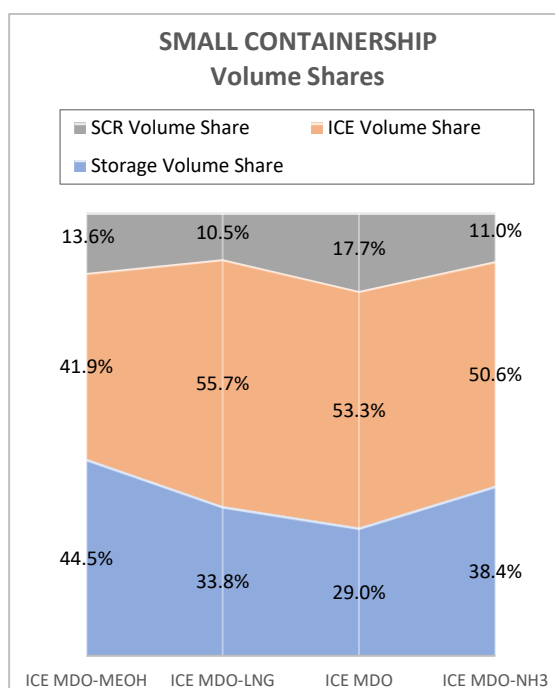
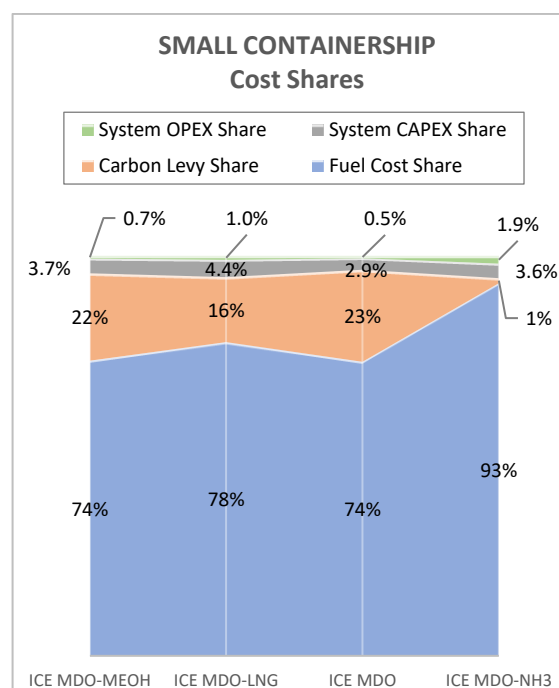


Figure 34: Score results from the multi-criteria analysis applied to the small container vessel case study



	Total Volume
DF-ICE MDO-MeOH	497 m ³
DF-ICE MDO-LNG	643 m ³
ICE MDO	382 m ³
DF-ICE MDO-NH3	617 m ³

Figure 35: Different volume item shares of the total volume for all technologies.



	Total Yearly Cost
DF-ICE MDO-MeOH	9.28 M\$/yr
DF-ICE MDO-LNG	10.59 M\$/yr
ICE MDO	11.22 M\$/yr
DF-ICE MDO-NH3	10.57 M\$/yr

Figure 36: Different cost item shares of the total volume for all technologies.

In this case, it is evident that MeOH- and MDO-fuelled solutions emerge as the most suitable options. If the relevance of volume and weight remains unchanged compared to the large container ship, the required amount of fuel—due to the reduced operational power and range—makes storage less impactful on the total volume, as shown in [Figure 35](#). This balances both the absolute volume and weight values associated with the storage system. In fact, the power unit (PU) now represents the largest volume share. However, in terms of absolute values, the differences between technologies are not significant.

Regarding cost shares, the same trend observed in the previous case study is confirmed, with fuel cost and the carbon levy remaining the primary cost drivers ([Figure 36](#)). Therefore, the previous considerations remain valid in this context.

For smaller container vessels, which navigate closer to environmentally sensitive areas, the emissions score has been increased from 1 to 3 to model a more realistic scenario. This adjustment gives greater weight to emissions, improving the scores of LNG (for NO_x emissions) and ammonia (for GHG emissions). Consequently, the increased emphasis on emissions and the lower energy requirements make ammonia a more competitive solution.

However, as in the previous case, future carbon levy policies and fuel prices will ultimately determine the preferred technology among the options analysed.

The final case study examines a large cruise ship, selected for evaluation due to its substantial power requirements and significant emissions impact, which position it as one of the most environmentally sensitive ship types. As in the previous case studies, volume and cost remain the most critical parameters.

Specifically, since the available space for guests directly impacts the ship's revenue, a volume relevance score of 4 has been assigned, allowing some flexibility in this regard if compared with container vessels. However, the relevance of cost has been kept at the highest level (5).

In this context, [Figure 37](#) presents the overall scores obtained, while [Figure 38](#) and [Figure 39](#) illustrate the volume and cost shares, as demonstrated in the earlier case studies.

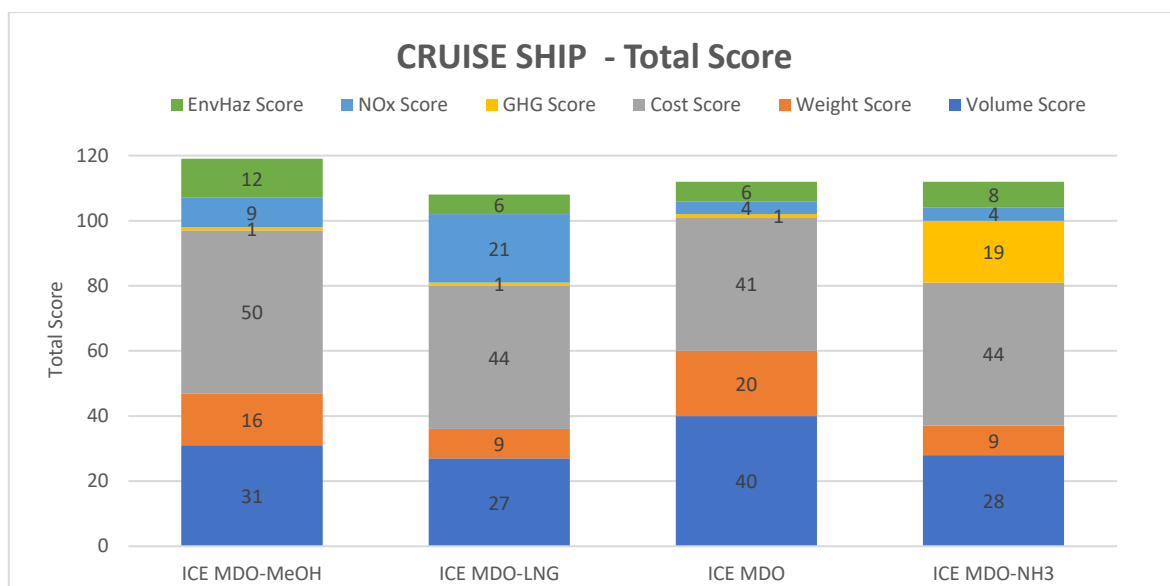
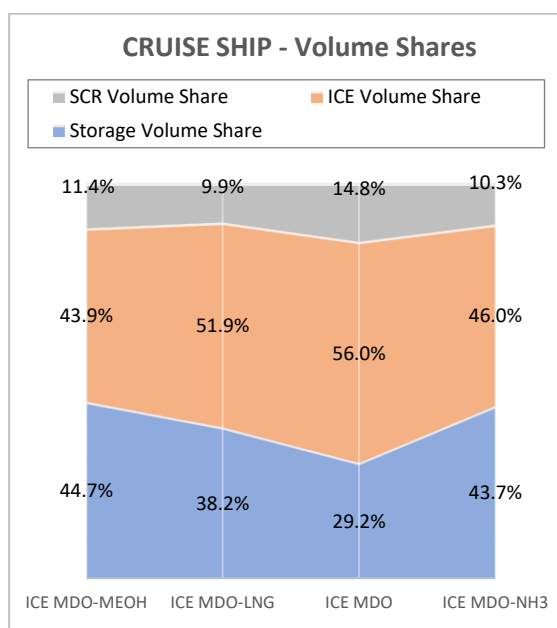
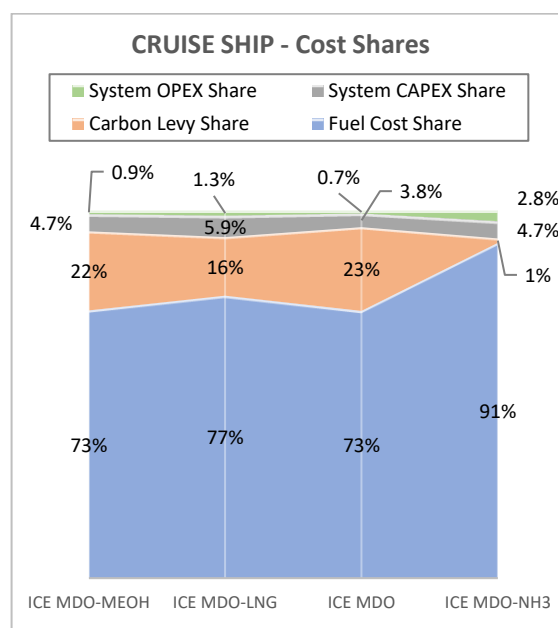


Figure 37: Score results from the multi-criteria analysis applied to the large cruise ship case study



	Total Volume
DF-ICE MDO-MeOH	2,539 m ³
DF-ICE MDO-LNG	2,924 m ³
ICE MDO	1,953 m ³
DF-ICE MDO-NH3	2,792 m ³

Figure 38: Different volume item shares of the total volume for all technologies.



	Total Yearly Cost
DF-ICE MDO-MeOH	30.19 M\$/yr
DF-ICE MDO-LNG	34.68 M\$/yr
ICE MDO	36.45 M\$/yr
DF-ICE MDO-NH3	34.69 M\$/yr

Figure 39: Different cost item shares of the total volume for all technologies.

As can be observed in [Figure 37](#), the most promising solution is represented by the MeOH-fuelled ICE. For this technology, the highest score is attributed to cost, primarily due to the low price of MeOH considered in the analysis.

From a volumetric perspective, it is evident that, for the reasons previously highlighted, MDO-fuelled solutions emerge as the most suitable technology. In this case as well, volume shares follow a trend similar to that of small container vessels, positioning the power unit as the key driver. This scenario is characterized by the high installed power considered (60,200 kW) and the limited operational range, which translates into a reduced amount of alternative/conventional fuel that needs to be stored. As a result of this lower volume requirement, the impact of the volume score on the overall results is less significant compared to previous case studies, preventing ICE MDO from being identified as the most promising solution.

Given the high sensitivity to emissions—where the relevance is set to 4 for GHG emissions and 5 for NO_x—ammonia and LNG emerge as viable alternatives comparable to MDO, providing a valid solution for this type of vessel.

Finally, in terms of cost, the shares remain largely unchanged compared to small container vessels, with fuel price being the primary determining factor, followed by the carbon levy. This further confirms the uncertainties associated with potential fuel price fluctuations, which play a decisive role in the final choice.

3.4. Limitations of Multicriteria Software and Further Needed Assessment.

As previously demonstrated through various selected case studies, the adapted Multi-Criteria Approach provides valuable insights into identifying the most promising technology for a preliminary and general evaluation. Despite the potential of this method, certain limitations must be addressed to achieve more detailed and accurate results. The main inconsistencies identified are discussed below.

- **Parameters should be defined following a more integrated approach.**

The adapted Multi-Criteria Approach currently takes into account the technical parameters of various system components. This methodology was adopted because the database is based on commercially available solutions. When implementing alternative fuels, it is essential to consider specific safety requirements, such as the need for additional void spaces (e.g., cofferdams) or enhanced safety systems, compared to conventional fuels. This could affect in a consistent manner the volume, weight and cost parameter, having an effect on the final score as well.

Consequently, this assessment cannot be performed entirely independently of regulatory frameworks.

- **Lack of Safety as parameter.**

Safety is the most critical factor to consider when integrating hazardous fuels on board. However, quantifying safety in a consistent manner for implementation within a multi-criteria approach presents significant challenges. Specifically, for certain alternative fuels such as ammonia or hydrogen, classification societies provide different guidelines based on the IGF Code, resorting to the “alternative design” approach.

This methodology aims to achieve a defined level of safety by applying various possible measures. Consequently, all technologies must collectively ensure the same safety standard, complicating the assignment of a safety score based solely on the chemical and physical properties of the fuel. Due to the inherent difficulty in quantifying safety as a parameter, it has been treated separately from the multi-criteria framework.

This underscores the importance of understanding the potential risks associated with fuel characteristics and the mitigation measures that can be adopted. Such evaluations are best conducted through a comprehensive risk assessment.

- **Higher parameter influence detailing level.**

As previously explained, relevance are used to model the relative importance of different key parameters. Despite this approach works effectively at a general level, it lacks flexibility. Specifically, focusing on the fuel storage system—which, for large vessels, represents the main component in terms of volume and weight—can result in varying degrees of cargo loss depending on the vessel's fuel preparation level. This, in turn, determines the necessary interventions for fuel switching, starting from the baseline configuration.

Currently, there are no standardized definitions for the “alternative fuels” preparation level assignation; however, different guidelines have been established to assess a vessel's readiness for alternative fuels.

In its most recent update on the topic, dated September 2024, American Bureau of Shipping (ABS) identifies three levels of “alternative fuel” readiness: Level 1-C (Concept Design Review), Level 2-D (Detailed Design Review), and Level 3 (Installation) [63]. Each level specifies distinct design requirements, assessments, and necessary documentation.

Another framework for categorizing preparation levels, offering a broader summary of required criteria, has been proposed by Lloyd’s Register [64], as illustrated in **Figure 40**. This framework defines five levels, where a higher level corresponds to a lower degree of “alternative fuel” readiness for the vessel.

Readiness standard		Criteria			
	Name	Description	Capabilities	Additional requirements	Comments
1	Near net zero GHG vessel	Capable of bunkering and operating for all onboard energy usage in all operating modes.	All required equipment installed and commissioned	Capabilities apply to all energy sources onboard Cannot be powered by fossil fuels	-
2	Low GHG vessel	Capable of bunkering and operating for primary propulsion in majority of operating modes.	All required equipment installed and commissioned	Capabilities apply to primary propulsion	Fossil pilot fuels acceptable Dual/multi fuels acceptable
3	Conversion under preparation	Primary propulsion capable of using fuels in scope. Some key components already installed but not yet commissioned.	Minimum requirements: • Engine retrofitted for fuel in scope, • Fuel storage tank in place	Capabilities apply to primary propulsion	-
4	Designed for conversion	Fossil fuel vessel with high level or detailed design for conversion.	-	Capabilities apply to primary propulsion	Detailed design is preferred to high level Ideally costings for conversion provided
5	Potential for conversion	Fossil fuel vessel with main engine that could use a fuel in scope, if retrofitted.	-	Retrofit pack available for main engine	Will become the norm as dual or multi fuel engines become the default
-	Fossil fuel only	Has no possibility of retrofit.	None	None	-

Figure 40: Lloyd's Register "alternative fuels" readiness level framework

A further distinction was conducted by the *Maersk Mc-Kinney Møller Centre* through a techno-economic study analysing the conversion of a 15,000 TEU container vessel to operate on MeOH and NH₃ [65]. As illustrated in **Figure 41**, the classification spans from a minimum level (Level 0), representing an existing vessel with no preparation for alternative fuels, to a maximum level (Level 4), which denotes a newly built vessel fully equipped to operate on both conventional fuel oil and alternative fuels.

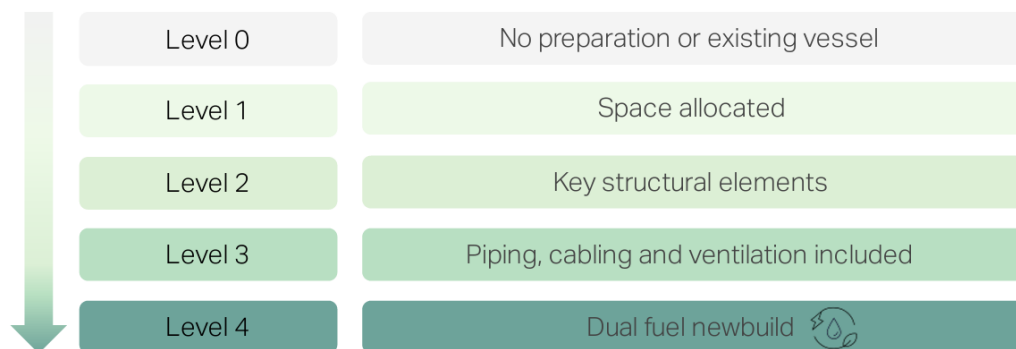


Figure 41: Moller-Maersk "alternative fuels" preparation level framework

Although definitions of readiness may vary, one of the main steps in transitioning from conventionally fuelled vessels to “alternative fuel-ready” vessels, is the allocation of space for systems required by alternative fuels. The preliminary allocation of space can lead to substantial space savings for certain vessel types (e.g., container ships) and enable cost-effective retrofitting interventions. This issue was quantified by *Møller-Maersk* in the above-mentioned study [65]. Specifically, during the conversion from fuel oil (FO) to MeOH, the loss of cargo capacity necessary to maintain the same operational range spans from 240 TEU, with a preparation level of 1 to 3, to 610 TEU when a Level 0 baseline is used. For NH₃, the scenario differs. Only a preparation level of 4 minimizes the loss of cargo to 540 TEU, whereas levels 0 to 3 would result in a loss of 1,100 TEU. This disparity between MeOH and NH₃-fuelled vessels arises because MeOH can be stored in tanks previously used for FO with minor modifications, while NH₃ requires specialized storage tanks. Consequently, only the highest preparation levels significantly mitigate cargo losses.

Furthermore, certain vessel types may have available space on the main deck, allowing the storage system to be installed outdoors. This can potentially minimize or even eliminate the impact of fuel tank volume, at least from a spatial perspective.

These considerations are not appropriately accounted for in the current Multi-Criteria Approach. Therefore, a more detailed assessment is necessary to evaluate the real impact of alternative fuel technologies based on vessel type and specific scenarios, whether for retrofits or newbuilds.

3.5. Outcomes of the Multicriteria Analysis.

Downstream of the results obtained through the adapted multi-criteria analysis, it is evident that this approach can serve as a valuable preliminary pathway for assessing the feasibility of a given technology onboard. However, as highlighted by the analysis, significant uncertainties remain

associated with this evaluation, necessitating further in-depth studies. Some of these uncertainties can be mitigated by refining the logic of the multi-criteria approach. Specifically, since future decisions will be governed by regulatory constraints and economic factors, all key parameters should be consolidated and quantified in terms of costs and compliance with upcoming regulations.

Nonetheless, the most significant uncertainties remain tied to future market conditions, particularly fuel prices and the carbon levy. As highlighted in the analysis, fluctuations in these prices can significantly impact the results, especially when cost sensitivity is high. For instance, in the case of grey ammonia and grey methanol, their associated technologies appear comparable to conventional solutions due to their lower costs. However, the use of grey methanol and grey ammonia does not address the emissions issue, as a well-to-wake (WtW) assessment—excluded from this analysis—would reveal substantial emissions during the fuel production phase. A more sustainable approach should consider e-MeOH or bio-MeOH, as well as e-NH₃ or blue-NH₃. Although there are currently no definitive bunker price values for these fuels [66], projections indicate a significant cost increase, further underscoring the necessity of a substantial rise in carbon levies to make green MeOH/NH₃-fueled solutions economically competitive with conventional alternatives.

Considering a Tank-to-Wake (TtW) approach, modelled using the adapted multi-criteria analysis, the comparability of alternative fuels such as NH₃, LNG, and MeOH is particularly evident in vessels where large storage capacity is not required, thus minimizing the impact of volume constraints. As a result, small containerships and cruise ships emerge as the most suitable candidates for alternative fuels, while large container vessels, which demand extended range and higher power output, still favour conventional solutions. Notably, cruise ships are strong candidates for ammonia implementation. This finding, combined with the absence of a dedicated safety parameter in the multi-criteria analysis, highlights the critical need to address safety concerns—especially important for passenger vessels. Therefore, further in-depth studies are necessary for all analysed ship types, with particular focus on cruise ships.

These findings confirm that while a multi-criteria approach is useful in the preliminary design phase—identifying promising options for both newbuilds and retrofits—it does not provide conclusive results. Both technical and economic aspects require further refinement, particularly given the uncertainties surrounding future market conditions, which remain the primary limitation in the reliability of these outcomes.

4. Further Considerations on Multicriteria Analysis: Regulatory Overview.

This chapter aims to provide a more in-depth analysis of the multi-criteria assessment results by reviewing the safety guidelines outlined in the IGF Code. It offers guidance on handling low-flashpoint fuels such as NH₃, MeOH, and LNG, while also incorporating insights from classification societies.

This analysis is essential when integrating potentially hazardous alternative fuels on board, particularly in contexts with stringent safety requirements, such as passenger vessels. The review has identified several critical areas where fuel leakage may potentially occur. Based on these findings, key safety measures have been defined in accordance with the established guidelines. This identification, along with the corresponding safety requirements, is fundamental in laying the groundwork for more detailed safety studies, such as risk analyses.

The key findings of this review indicate that, starting from an LNG-based case study, several regulatory requirements are extendable to ammonia and methanol. However, additional measures must be incorporated to account for the specific characteristics of these fuels. Furthermore, in this context, the "alternative design" approach must be adopted to ensure an equivalent level of safety compared to conventional applications. As required by the guidelines, this equivalency will be verified through a dedicated risk assessment. Ammonia handling has been considered within this study.

Regulatory aspects of marine applications are governed by the IMO from different perspectives. Regarding the focus of this study, the International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code) [67] is the main reference. Specifically, it has the purpose to provide an international standard for ships, other than vessels covered by the IGC Code [68], operating with gas or low-flashpoint liquids as fuel.

Based on this main general reference, several classification societies have made guidelines available, mostly aligned with the IGF Code standards. Only a few modifications are present, depending on the specific society.

The following overview took into account different sources, aligning the outcomes with the most commonly agreed requirements. [Table 19](#) presents all considered sources and relative reference.

Source	Update	Reference
IMO - IGF Code	June 2015	[69]
Bureau Veritas (BV)	January 2020	[70]
Det Norske Veritas and Germanischer Lloyd (DNV-GL)	July 2020	[71]
American Bureau of Shipping (ABS)	July 2020	[72]
Nippon Kaiji Kyokai (ClassNK)	2020	[73]
Registro Italiano NAVale (RINA)	May 2021	[74]
Korean Register (KR)	June 2021	[75]
Bureau Veritas (BV)	July 2021	[76]
Det Norske Veritas (DNV)	July 2021	[77]
Indian Register of Shipping (IRCLASS)	December 2022	[78]
American Bureau of Shipping (ABS)	September 2023	[79]
Nippon Kaiji Kyokai (ClassNK)	June 2024	[80]
American Bureau of Shipping (ABS)	July 2024	[81]
Bureau Veritas (BV)	September 2024	[82]
Lloyd's Register	July 2024	[83]
Lloyd's Register	July 2024	[84]

Table 19: Sources used for gathering safety measures information

4.1. Identification of Ammonia Spaces and Their Features.

Due to the toxicity of ammonia, it poses a serious hazard to human life. Therefore, minimizing the risk of leakage is crucial to preventing any critical situations.

In this context, it is essential to identify and categorize spaces where the fuel is present during normal operation, as these areas are the most sensitive. To this end, [Table 20](#) summarizes the key spaces identified based on both the IGF Code and the relevant classification society guidelines.

Hazardous Spaces
• Bunker Station (BS) • Tank Connection Space (TCS) • Tank Hold Space (THS) • Fuel Preparation Room (FPR)

Table 20: Hazardous Spaces identified by IGF Code and Classification Societies Guidelines

4.1.1. Bunker Station and Bunkering System.

The bunker station is a designated area for the bunkering system, serving as the connection point between an external fuel storage facility (e.g., onshore storage, barge or truck) and the vessel's fuel storage tanks during bunkering operations.

The bunker station is classified as a Hazardous Area Zone 1 in accordance with the IGF Code. This classification reflects the potential presence of flammable gases, liquids, or vapours during the normal operation of vessels, requiring that all electrical installations within the space be certified for use in potentially explosive environments. This, considering the high ammonia toxicity as well, highlights the critical importance of complying with safety regulations.

While it is recommended to install the station outdoors, if this is not feasible (e.g., on passenger vessels), a semi-enclosed or fully enclosed space may be considered, subject to a risk assessment and the implementation of a proper ventilation.

Both ammonia and fire detection sensors are required. Furthermore, the space is protected by a water spray firefighting system that activates either in the event of a fire, to extinguish the flames, and upon the detection of ammonia, to reduce its concentration in the area. Contaminated water resulting from the activation of the water mist system will be drained into a tank equipped with controlled venting (drain tank) by means of proper drip trays. In case of fire, additional suitable extinguishing media like chemical powder or appropriate foam can be adopted.

From a ventilation perspective, if a semi-enclosed or an enclosed space is considered, the ventilation system is designed to provide 30 air changes per hour (ac/h) to prevent the accumulation of potentially toxic or explosive vapours, allowing their proper extraction.

Some of the more recent regulations focusing on ammonia as a fuel mandate the installation of a water screen at the entrance. This measure is intended to minimize the leakage of gas into adjacent indoor spaces.

Each ship side requires one bunker station, and for each station, pipelines must connect to all storage tanks. Additionally, a secondary line is necessary to handle vapor return from the storage tanks during the filling process dependently to the relative ammonia storage conditions between the receiving vessel and the outboard storage.

Considering that the bunkering manifold is the weakest link in the fuel transfer chain, the various surveyed regulations—which build upon and specify the requirements of the IGF Code—

mandate the use of Emergency Release Couplings (ERC) or Break-Away Couplings (BAC) to prevent any potential external leakage in case of an emergency.

An additional measure that should be implemented to minimize or entirely prevent ammonia releases or spills during standard disconnection procedures is the Quick Connect/Disconnect Coupling (QCCD). This mechanism facilitates the safe and efficient connection or disconnection of the bunkering facility's hose system to the receiving vessel's manifold. A representation of a typical bunkering facility structure composed by a mechanical loading arm is shown in [Figure 42](#).

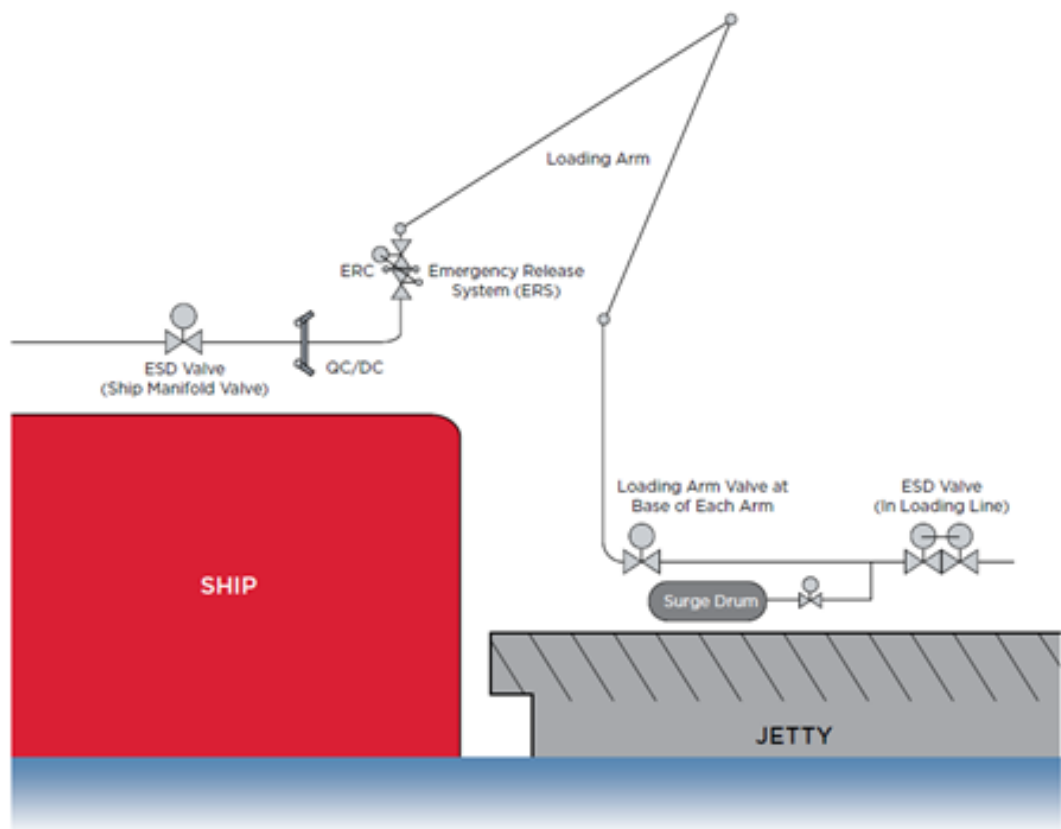


Figure 42: Typical mechanical loading arm

4.1.2. Tank Connection Space and Dedicated Systems.

Tank Connection Spaces (TCS) are dedicated areas located above each storage tank, housing all the essential components for ammonia transfer, including transfer valves, safety valves, and pump motors (transfer pumps). Similar to the bunker station, these spaces are classified as Hazardous Area Zone 1 due to the presence of ammonia. Consequently, as enclosed spaces, their

adjoining structures and passages must be designed to prevent the passage of liquids and gases, thereby mitigating the risk of fuel leakage into other indoor areas. Access to these spaces is provided through air-lock systems, and all electrical installations must be certified for operation in potentially explosive environments.

From a ventilation perspective, this space is designed to achieve the same bunker station's requirements to prevent the accumulation of potentially toxic or explosive vapours.

Within the TCS, sensors must be installed for both ammonia detection and fire detection (including flame, heat, and smoke detectors). Furthermore, the space is protected by a water mist fire suppression system, which can be activated either in the event of a fire to extinguish flames or upon detection of ammonia to reduce its concentration within the area.

Contaminated water generated by the activation of the water mist system will be drained into a controlled vented tank (drain tank) through a dedicated drainage piping system equipped with non-return valves.

4.1.3. Tank Hold Space and Storage systems.

The Tank Hold Space (THS) is the area designated for the allocation of storage tanks. It is classified as Hazardous Zone 1, except if type-C storage tanks are used for storing ammonia. This is due to the higher design standards required for this type of storage technology. In particular, requirements such as the inerting of THS become necessary only when the storage system requires a secondary barrier, either partial or complete. In the case of a partial barrier, the space may be filled with dry air, provided that systems are in place to promptly detect any gas leaks and inert the affected THS before a potentially explosive atmosphere can develop. However, if a Type-C tank is used, this requirement does not apply: in such cases, dry air alone is sufficient to prevent ice formation on the tank surfaces. When Type-C tanks are not employed, THS must be equipped with permanent gas detectors, while flame detection systems are always mandatory, regardless of the tank type used.

As illustrated in *Figure 43* [85], storage tanks can be classified as either independent or integrated. Independent tanks are self-supporting structures that must be installed within the ship's structure and securely connected to it. In contrast, integrated tanks, such as membrane tanks, are not self-supporting and rely on the ship's structure for support.

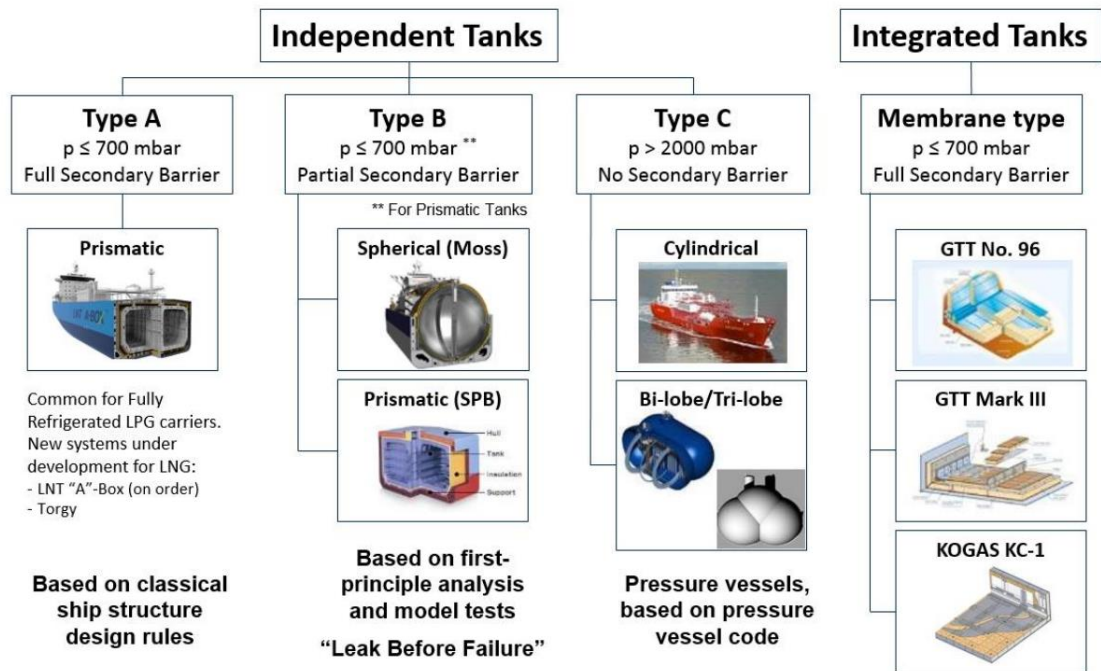


Figure 43: Different storage tank types usable for storing liquefied gases

In line with the aforementioned distinction, the regulations mandate different safety measures to ensure secure storage, depending on the type of tank. Among the additional safety systems directly associated with storage, secondary barriers can be required. According to the IGF Code, a secondary barrier is a liquid-resistant outer component designed to provide temporary containment for any anticipated leakage of liquid fuel from the primary barrier (tank wall). It also serves to prevent the ship's structure from reaching unsafe temperature levels. Regarding this item, The IGC Code, gathering rules for vessels carrying liquefied gases in bulk, admits the usage of ship structures as secondary barrier only if the liquefied gas temperature is not lower than -55°C . Therefore, ammonia allows this possibility. The space between primary and secondary barriers is defined as interbarrier whether or not completely or partially occupied by insulation or other material.

Another important safety system to consider when storing liquefied gases is the boil-off gas (BOG) management system. Even though storage tanks are insulated, it is impossible to completely eliminate heat transfer from the external environment. Consequently, pressure can build up inside the tank due to liquid evaporation and to the increase in gas temperature. To address this, depending on the type of tank, it is essential to implement a system capable of managing the excess BOG, thereby reducing the pressure within the storage tank. Regulations permit the use of different BOG management systems, including an ammonia combustion unit

for oxidation, an ammonia scrubber for dissolving ammonia vapours in sprayed water, an ammonia reliquefaction system for reliquefying the evaporated fuel, or a pressure accumulation.

In case of an emergency resulting in a uncontrolled pressure build up inside the tank, at least two pressure relief valve (PRV) systems must be present, except if a fully-pressurized type-C tank is used. These valves allows to discharge part of the BOG at the vent mast when the internal pressure rises over their setting value, ensuring that the tank is not damaged. PRVs need to be fitted in the highest part of the tank to avoid the direct contact with the liquid. As the IGF Code requires, the setting of the PRVs shall not be higher than the vapour pressure that has been used in the design of the tank.

Due to the toxic nature of ammonia, it is essential to account for a hazardous zone surrounding the vent mast outlet for safety reasons in case of venting event. Within this zone, no air intakes, outlets, or openings to accommodation spaces, service spaces, or control stations should be located. Regulations stipulate that this minimum distance must be either 25 meters or the ship's beam, whichever is smaller, and must also be observed in relation to other non-toxic and non-hazardous areas.

The previously implemented safety measures related to fuel storage depend on the specific storage technology employed onboard which are categorized based on the design methodology. Their main characteristics are outlined below.

- **Type A Tank**

Type A tanks (*Figure 44*) are independent, self-supporting structures primarily designed, as defined by the IGF Code, using conventional ship-structural analysis methods in compliance with the requirements set forth by the administration. These tanks are predominantly constructed with flat surfaces, and their design vapor pressure must not exceed 0.07 MPa. Consequently, liquefied gas stored in these tanks must be maintained at ambient pressure, with minimal allowable over-pressurization. When using this type of tank, both a complete secondary barrier and a redundant boil-off gas (BOG) management system are required. For ammonia stored at -33°C, the secondary barrier can be formed by the hull structure. Additionally, the interbarrier space must be equipped with an ammonia detection system and a mechanism capable of managing and depleting any potential leakage. This kind of tank allow a very good utilization of internal spaces.

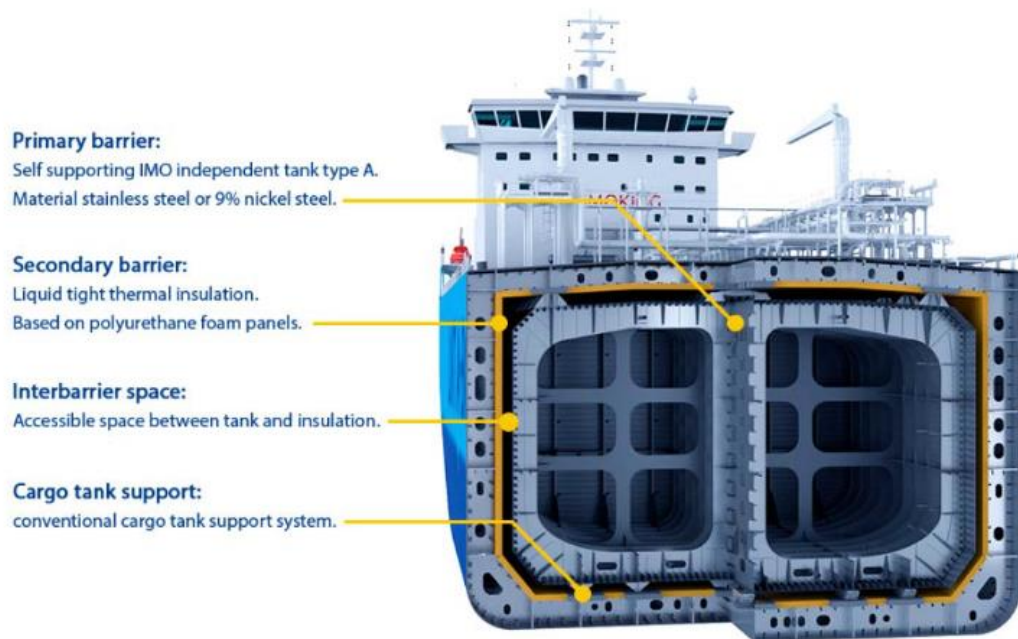


Figure 44: LNT A-box type A tank system for storing ammonia as bulk cargo [86]

- **Type B Tank**

Type B tanks ([Figure 45](#) and [Figure 46](#)) are another type of independent tank, typically spherical or prismatic in shape, used for storing liquefied gases. Unlike Type A tanks, Type B tanks are designed using model tests, advanced analytical tools, and detailed analysis methods to assess stress levels, fatigue life, and crack propagation characteristics.

For this type of technology, if the tanks are primarily constructed with flat surfaces, as in the case of prismatic tanks, the design vapor pressure must not exceed 0.07 MPa.

Additionally, as represented in [Figure 46](#), a partial secondary barrier with a protection system to stop spray reaching hull and leading liquid to drip tray for evacuation is required for this technology, along with a redundant boil-off gas (BOG) management system.

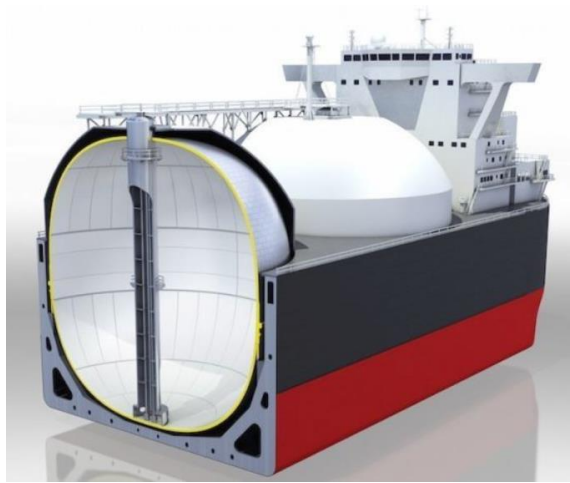


Figure 45: Type B tank rendering for storing LNG by Kawasaki Heavy Industry

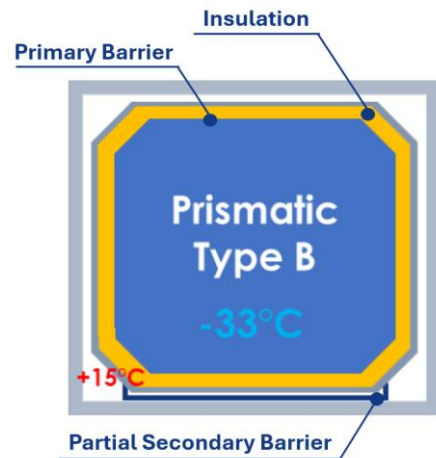


Figure 46: Typical prismatic type B tank layout proposed by LNT Marine for storing ammonia.

- **Type C Tank**

Type C tanks represent the final category of independent tanks. They are designed to store liquefied gases under cryogenic conditions and can withstand higher pressures. For this reason, they are typically cylindrical, bilobed, or trilobed in shape.

As defined by the IGF Code, their design is based on pressure vessel criteria, which are modified to incorporate fracture mechanics and crack propagation considerations. Since the design process for this type of vessel requires a more structured and comprehensive approach, Type C tanks are considered as more reliable and do not require secondary barriers. The BOG management system can be omitted if the type C tank is designed to withstand 18 bar, corresponding with the ammonia saturation pressure at 45°C.



Figure 47: Type C tank for storing liquid ammonia

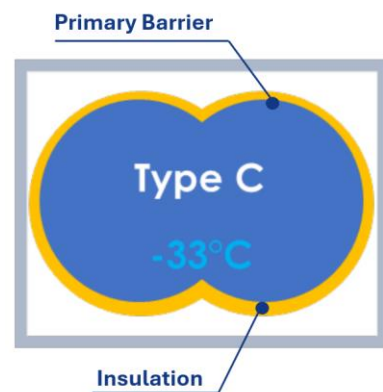


Figure 48: Type C tank layout proposed by LNT Marine for storing ammonia

- **Membrane Tank**

Membrane tanks are integrated tanks designed to store liquefied gases. They are constructed by lining the hull structures with specialized membranes, ensuring sufficient insulation capacity. Depending on the provider's product, the tank configuration can feature either a single membrane or a double membrane design. The first type, illustrated in [Figure 49](#), consists of only a primary barrier, represented by the internal membrane, directly in contact with the liquefied gas. In this configuration, the hull itself serves as the secondary barrier. In compliance with regulatory requirements, this design is suitable for liquefied gases with temperatures above -55°C .

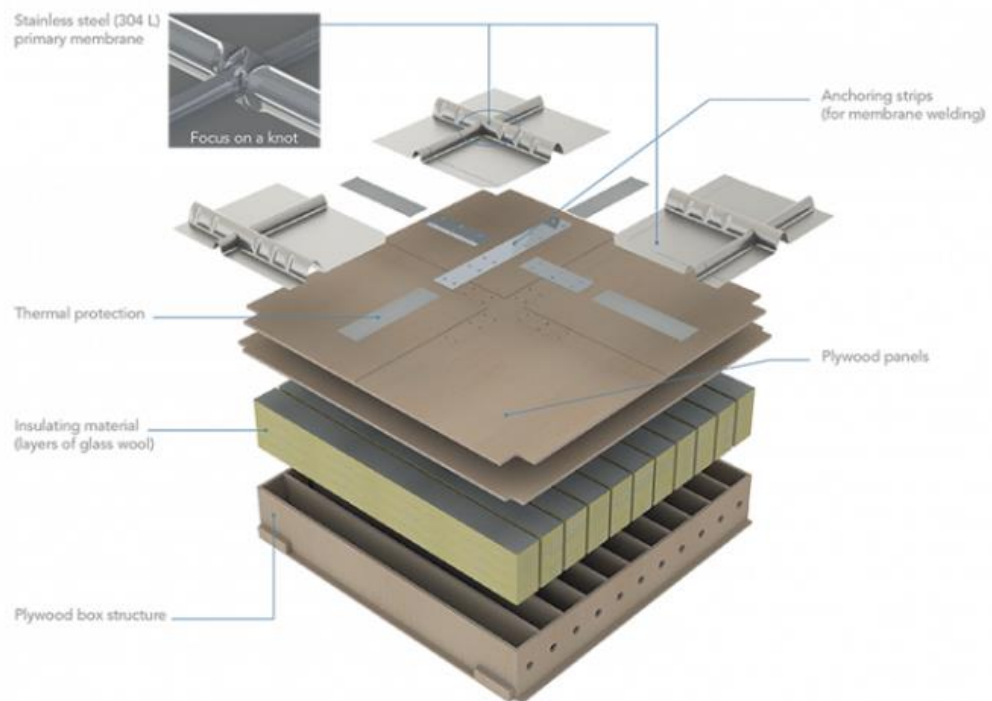


Figure 49: GTT MARS membrane tank layout for storing LPG [87]

Conversely, the second layout ([Figure 50](#)) incorporates two distinct membranes that function as primary and secondary barriers. This configuration is typically employed for the storage of LNG, which is maintained at a temperature of -162°C .

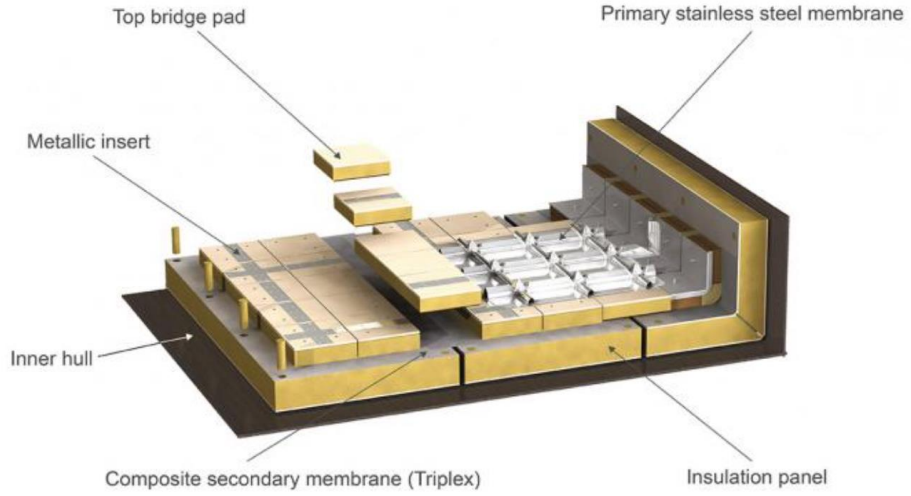


Figure 50: GTT MARKIII membrane tank layout typically used for storing LNG [88]

Regarding their design, it must account for thermal and other types of expansion or contraction, ensuring these factors are managed without compromising the membrane's tightness, as required by the IGF Code.

The design vapor pressure should not normally exceed 0.025 MPa. However, if the hull scantlings are adequately reinforced and due consideration is given to the strength of the supporting thermal insulation, the design vapor pressure may be increased to a maximum of 0.07 MPa.

Like Type A tanks, membrane tanks require both a complete secondary barrier and a redundant boil-off gas (BOG) management system.

In the context of storage, another important parameter, as defined by the IGF Code and endorsed in its definition by various classification societies, is the Loading Limit, identified in (5). This parameter represents the maximum permissible filling level for storage tanks containing liquefied gas. It is determined based on the thermochemical characteristics of the bunkering fuel and the storage conditions.

$$LL = FL \cdot \frac{\rho_R(T_R)}{\rho_L} \quad (5)$$

Where:

- FL = Filling Limit representing the maximum liquid volume in a fuel tank relative to the total tank volume when the liquid fuel has reached the reference temperature. It is equal to 98%
- ρ_R = Relative Density of fuel at the reference temperature (T_R)
- ρ_L = Relative Density of fuel at the loading temperature.
- T_R = Reference Temperature corresponding to the vapour pressure of the fuel in a fuel tank at the set pressure of the pressure relief valves

From the previous definition, given an ammonia bunkering temperature of -33°C and a FL of 98%, it was possible to calculate the LL trend as a function of the PRVs set pressure. *Figure 51* displays this trend, highlighting a maximum filling of 82% for a fully pressurized Type-C tank at 18 bar(a). This highlights the significant impact that LL can have on the ship's range, depending on the choice of storage technology.

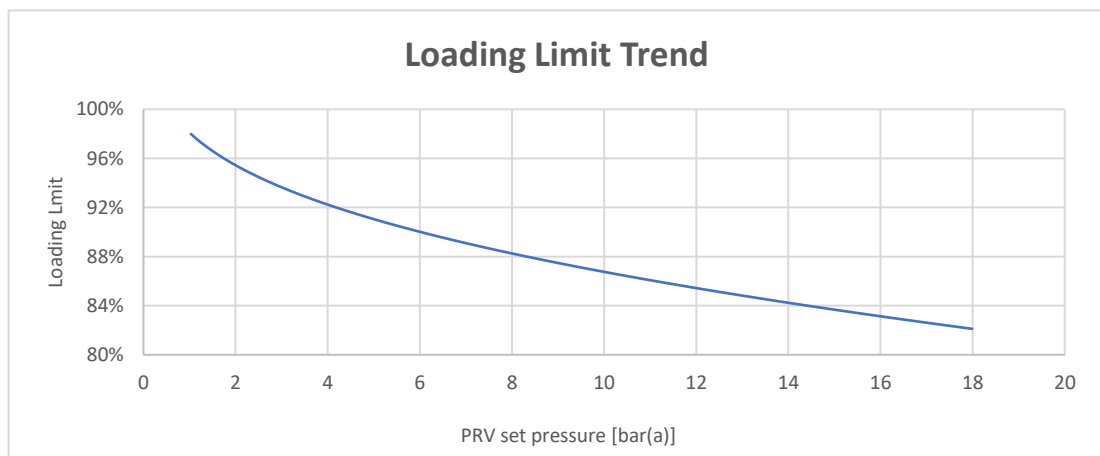


Figure 51: Trend of the Loading Limit as a function of the PRVs' set pressure

4.1.4. Fuel Preparation Room and Low Flashpoint Supply System.

The Fuel Preparation Room (FPR) is the area where fuel is processed before being supplied to the engines through the Ammonia Fuel Supply System (AFSS). Similar to the TCS, this room is classified as Hazardous Zone 1, and as such, its adjoining structures must be impermeable to liquids and gases. Access must be restricted and available only via air-lock systems. Additionally, under normal operating conditions, the room must remain unmanned.

From a ventilation perspective, same previous consideration can be applied.

The FPR is equipped with sensors for ammonia detection as well as fire detection systems (including flame, heat, and smoke detectors). As TCS, it is protected by a water mist fire suppression system that is activated automatically in the event of a fire to extinguish flames or upon the detection of ammonia to reduce its concentration within the room. Activation occurs automatically when ammonia concentration exceeds a specific threshold (e.g., 30 ppm, as defined by certain standards such as BV) and can also be triggered manually from inside or outside the room.

Contaminated water resulting from the activation of the water mist system is drained into a drain tank via a dedicated drainage system.

Fuel is delivered to the FPR directly by submerged impeller pumps (transfer pumps) located in the storage tanks. Furthermore, each FPR on board must be connected to all storage tanks and engines, ensuring maximum operational flexibility for the fuel supply system.

Regarding the systems to be installed in this space, the Ammonia Fuel Supply System (AFSS) must ensure fuel quality in terms of purity, temperature, and pressure for engine supply. To achieve this, the system primarily consists of redundant heat exchangers, high-pressure pumps, filters, and a catch tank, which serves as a buffer for the engine return line. In addition the AFSS requires the connection to a purge gas treatment system for ensuring safety line freeing operations when the fuel injection need to be interrupted. *Figure 52* illustrates an example of an AFSS designed for liquid ammonia supply and injection (A-LFSS) provided by Wartsila [89].

Liquid Ammonia Fuel Supply System

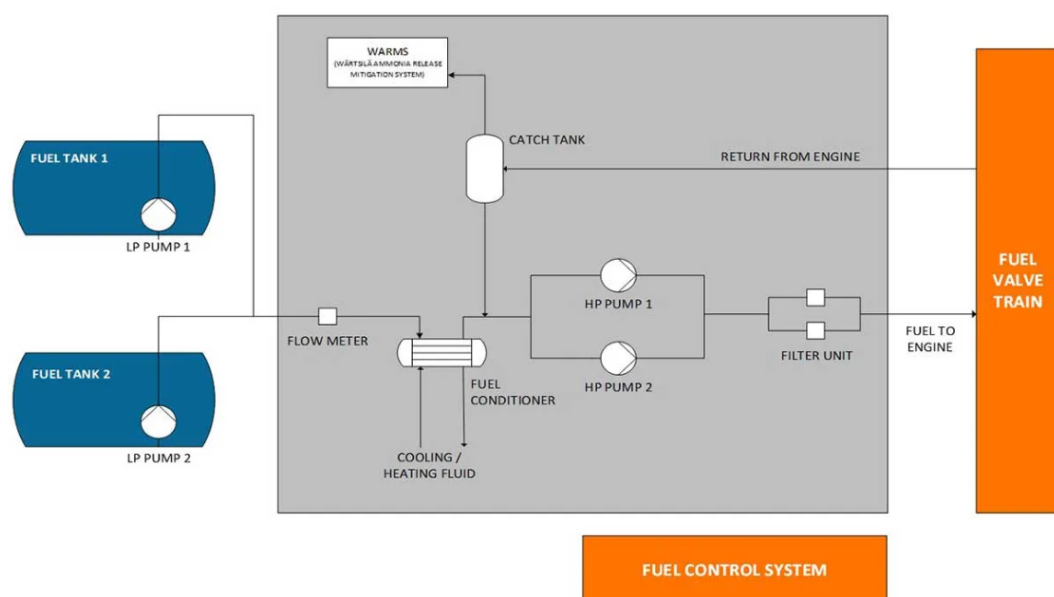


Figure 52: Wartsila's A-LFSS layout

As shown in [Figure 53](#), the same provider envisions the possibility of utilizing different ammonia fuel supply systems (A-LFSS or A-FGSS) depending on the type of injection required.

Integrated Ammonia Fuel System

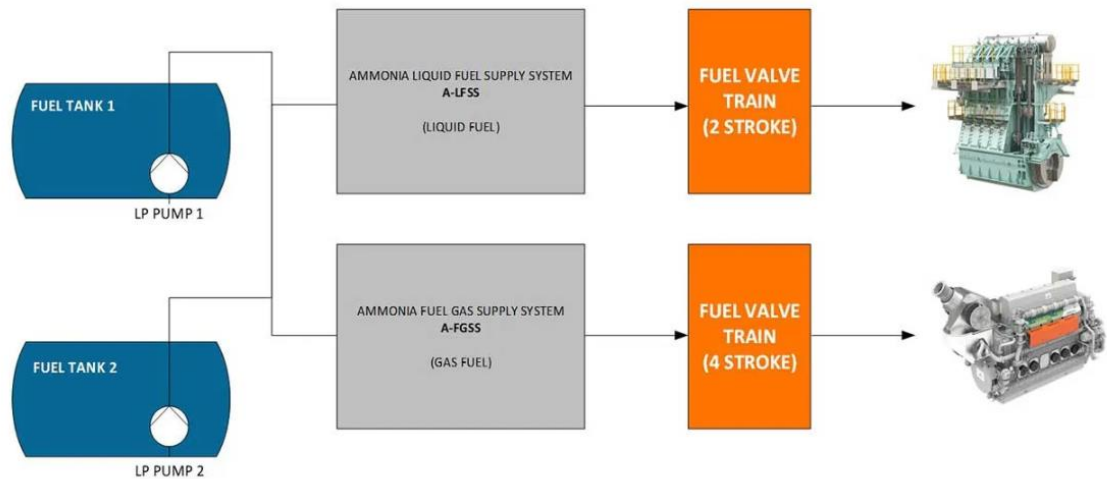


Figure 53: Different AFSS possibilities depending on the fuel injection type

A further system featured in FPR is the Boil-Off Gas (BOG) treatment system, which is discussed in greater detail in the dedicated chapter. Depending on the type of storage and whether regulations require it, the system may include a mechanism capable of managing the boil-off gas (BOG) generated by the evaporation of fuel within the storage tanks. The BOG treatment system is also identically replicated in both FPRs.

5. Focus on Fuel Storage Comparison: Safety and Economic Aspects.

This chapter focuses on the primary component of alternative fuel systems in large vessels: the storage system. Given the high toxicity of ammonia, a comprehensive techno-economic assessment, with particular attention to safety considerations, requires a thorough understanding of the thermodynamic behaviour of large-scale fuel storage tanks. To this end, an initial review of cryogenic tank modelling approaches has been conducted, alongside an overview of existing studies, primarily focused on LNG and LH₂. This analysis aims to establish the state of the art and identify the most suitable modelling approach that balances generalization requirements with predictive accuracy. The proposed model is designed to simulate multiple case studies by varying geometrical characteristics, stored fuel types, and operational conditions, including liquid mass flow extraction for engine feeding and BOG processing via a reliquefaction system. Finally, the model has been applied to containership and cruise vessel case studies to evaluate different operational scenarios based on the distinct characteristics of these vessel types.

Due to the high toxicity of ammonia, it is crucial to minimize the possibility of its release, whether through a venting event or as a result of pipelines gas freeing, as better highlights by the successive risk analysis. In light of this necessity, evaluating the behaviour of the storage system under various potential operating conditions becomes highly important. A storage tank, in particular, must be one of the safest components of the fuel system. Given the large quantity of fuel it stores, simulating potential behaviours that could lead to critical issues, such as ammonia venting or tank structural damages, it is essential to prevent such incidents or implement corrective measures (e.g., installing a proper BOG management system).

To address these challenges, a model has been developed to simulate the behaviour of the storage tank under various operational conditions. The goal of model development is to achieve a good balance between high accuracy and the ability to generalize across different fuels, tank dimensions, shapes, and operating conditions.

Operating conditions, in this context, refer to the ability to extract a fuel mass flow rate from the storage tank to meet engine demands corresponding to different power outputs. By managing this aspect, the model can simulate scenarios such as maximum overpressure under sealed conditions—

if the mass flow is set to zero—or potential warning situations arising from under-pressurization of the vessel.

The sealed condition scenario illustrates the build-up of pressure and temperature under inactivity conditions, emphasizing the need for effective BOG management to prevent venting during normal operations. In this context, also non-conventional conditions as a fire event, can be simulated. In fact a fire in a space adjacent to the storage system could result in a rapid temperature increase. This, in turn, would lead to significant heat transfer to the storage tank, causing accelerated evaporation of its contents and an internal temperature and pressure quick build-up. Under these circumstances, the BOG management system might not suffice to maintain pressure below the MARVP, potentially triggering the opening of the PRVs and leading to ammonia venting through the vent mast. Such a scenario is classified as an emergency event.

In contrast, the scenario where an outgoing mass flow is considered aims to simulate the possibility of high engine fuel demand leading to a decrease in internal saturation pressure and temperature. In this context, the heat transfer from the surrounding environment may be insufficient to evaporate the additional amount of extracted fuel. Consequently, the system will attempt to increase evaporation by absorbing heat from within, potentially inducing an evaporative cooling effect.

This scenario could result in vacuum conditions, reducing the saturation pressure below critical levels and potentially compromising the tank's integrity.

As with overpressure, vacuum scenarios are influenced by the specific characteristics and design features of the tank. At the same time, these features also determine the holding time in a self-pressurization scenario, making them a key factor in defining the boil-off rate (BOR).

5.1. Literature Review on Cryogenic Storage Models.

As a first step, a literature review was conducted from two different perspectives. The first focuses on the available approaches that can be utilized to simulate the behaviour of bi-phase cryogenic storage systems, while the second examines existing studies to assess how many usable models are already available in the literature, specifically concerning LNG, LH₂, and NH₃.

Both perspectives are of significant importance during the research phase. Specifically, understanding existing methodologies has been deemed crucial, as it enables the categorization of models into various groups and the identification of the most accurate approach achievable without compromising the model's generalization potential.

5.1.1. Overview on Logic and Type of Cryogenic Storage Models

The evaluation of the behaviour of bi-phase cryogenic storage systems requires a thorough assessment of the thermodynamic phenomena occurring within. Considering ammonia, which has a boiling point of approximately -33°C (239.14 K) at atmospheric pressure, and assuming the absence of extremely low external temperatures—uncommon in maritime environments—an influx of heat from the surroundings is inevitable. This heat transfer alters the internal energy of the storage system, which, depending on the quantities of liquid and vapor stored, will lead to an increase in pressure and temperature. This process continuously changes the internal thermodynamic characteristics of both phases over time. This behaviour is particularly evident when the storage operates under sealed conditions, resulting in the self-pressurization phenomena.

Various categories of models have been identified and analysed to describe this behaviour effectively.

A comprehensive review of the available models has been conducted by Wang et al. [90], focusing on LH_2 self-pressurization modelling. This study categorizes the models into two main groups: Thermal Equilibrium Models (TEM) and Non-Thermal Equilibrium Models (NTEM). As illustrated in [Figure 54](#), various model classes can be assigned to these categories.

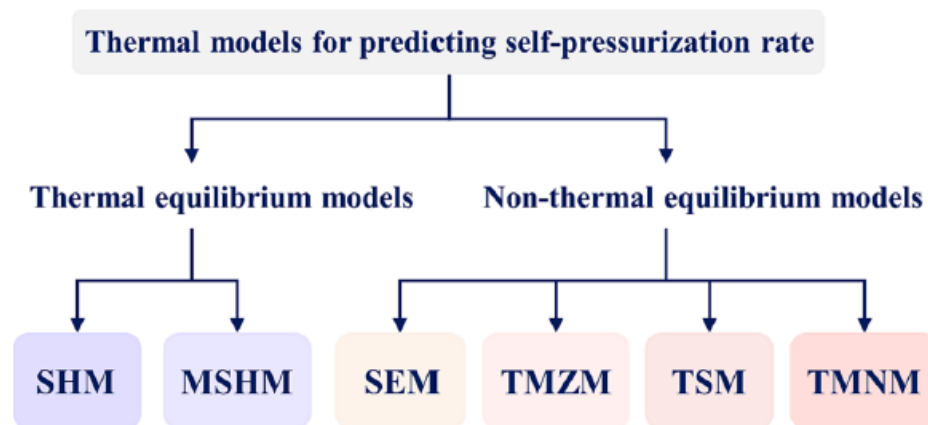


Figure 54: LH_2 self-pressurization model categories [90]

The TEM assumes that the vapor and liquid phases in an LH_2 tank are in thermal equilibrium, meaning no temperature gradient exists. It simplifies calculations by neglecting non-equilibrium heat and mass transfer. Due to its simplicity, TEM is used to predict the self-pressurization process. This makes it a practical choice for preliminary calculations. It is commonly applied to estimate the holding time of cryogenic tanks, presenting high generalization potential.

On the other hand, NTEM enables a higher level of detail by treating the liquid and vapor phases separately. This approach allows for the consideration of temperature gradients within both phases, thereby improving prediction accuracy. As a result, the interaction between the two phases, driven by their differing thermodynamic conditions, must be modelled at the interface. In this regard, the layer theory is commonly employed to estimate the evaporated mass through an interface energy balance. Furthermore, the heat exchanged between the liquid and vapor phases at the interface involves convective heat transfer, which, in more detailed models, is extended within the phases due to the stratification phenomenon. While this type of model provides more accurate results for self-pressurization, the definition of convective heat exchange coefficients presents limitations in terms of generalization, both with regard to storage geometry and operational conditions.

The main hypotheses and working schemes of all modelling approaches are outlined as follows.

- **Saturated Homogeneous Model (SHM)**

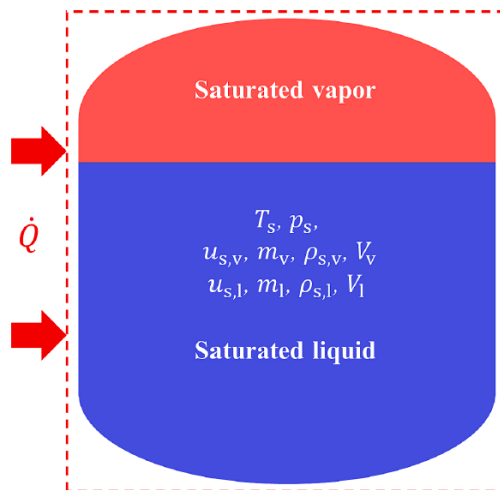


Figure 55: Schematic of SHM [90]

The SHM class is widely used in the self-pressurization process, particularly for calculating pressure rise during the filling and transport of cryogenic fluids. This model treats the entire plenum as a single control volume (Figure 54), without distinguishing between the different phases. In this approach, the temperature inside the storage tank is assumed to be uniform and corresponding to saturation. However, this assumption does not allow for a

direct evaluation of the evaporated mass which can be indirectly estimated by measuring the quality variation between subsequent thermodynamic conditions.

Therefore, main assumption taken into account from the SHM are listed below, as reported in [90].

- The vapor and liquid are continuously in thermal equilibrium and saturation.
- The total volume of the tank is constant.
- The LH₂ is non-venting stored until the pressure reaches its maximum allowable value or the liquid fill ratio reaches the critical value.

- **Modified Saturated Homogeneous Model (MSHM)**

To increase the level of detail in the SHM, a modified approach has been proposed that aligns previous outcomes with experimental data from various cryogenic fluids through dimensionless polynomial fitting [90]. This model enables the correction of SHM results; however, its generalization is significantly limited due to the absence of polynomial functions for different substances and constraints in the operability range.

- **Surface Evaporated Model (SEM)**

The SEM class is the simplest Non-Thermal Equilibrium Model (NTEM). It accounts for the distinction between liquid and vapor phases, as shown in [Figure 56](#), but introduces a simplification in energy distribution. Specifically, all heat leakage into the liquid phase is assumed to contribute directly to evaporation, driving the phase change process.

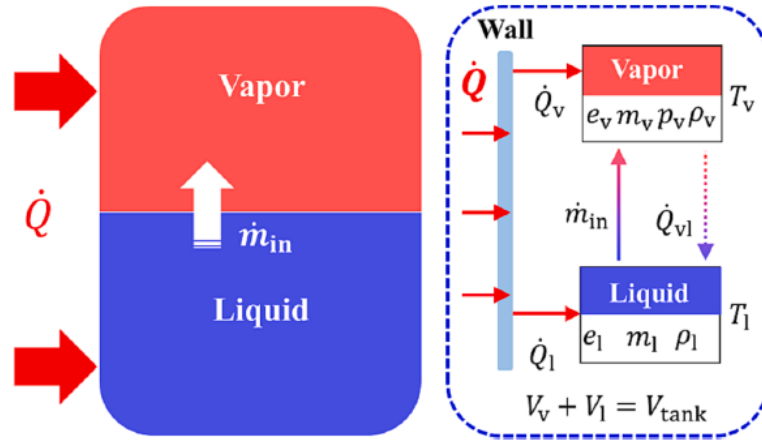


Figure 56: Schematic of the mass and energy exchange process for the SEM [90]

As reported in [90], main assumptions for this type of model are listed as follows.

- The vapour and liquid are both initially saturated
- The heat leakage into the liquid converts to the mass transferred into the vapor
- The temperature and density of the liquid is constant in the self-pressurization process.

- **Thermal Multi-Zone Model (TMZM)**

Like the SEM, the Thermal Multi-Zone Model (TMZM) distinguishes between liquid and vapor phases. However, it introduces a vapor-liquid interface to provide a more detailed representation of the self-pressurization process within the plenum. This model specifically incorporates convective heat exchange between the two phases, applying an energy balance at the interface, which is always maintained at saturation conditions. In contrast, the liquid and vapor phases are considered subcooled and superheated, respectively. The evaporated mass is directly determined from the energy balance at the interface, modelled using layer theory, which treats the interface as a control volume with negligible mass, allowing for the application of only the energy balance. A graphic representation on the working principles is reported in [Figure 57](#).

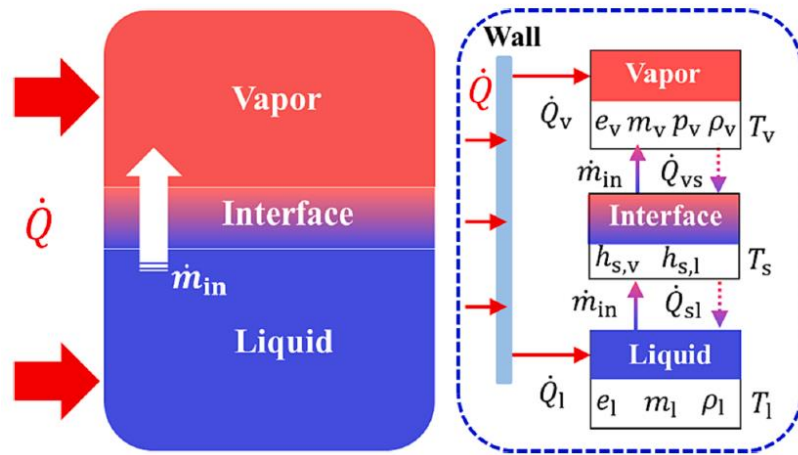


Figure 57: Schematic of the mass and energy exchange in different zones for the TMZM [90]

Following previous considerations, the main assumptions of TMZM can be resumed as follows [90].

- The vapor is superheated and the liquid is saturated or subcooled.
- The vapor-liquid interface is a saturated and thin film with negligible mass.
- The vapor and liquid are in phase equilibrium.

- **Thermal Stratified Model (TSM)**

The Thermal Stratified Model (TSM) accounts for flow and energy exchange within the boundary layer near the inner tank walls while analysing the evolution of thermal stratification in the storage system. This model is based on the principle that liquid in contact with the warmer tank surfaces heats up and rises toward the vapor-liquid interface. As a result, a stratified layer with a temperature gradient forms near the interface. This process is represented in [Figure 58](#). A critical aspect of TSM is the selection of appropriate correlations to determine the thickness of this stratified layer. While this approach enhances the model's accuracy, its applicability is limited. The correlations, typically derived from free convection, are highly dependent on the tank's geometry, fluid properties, and sealed conditions, making the model not suitable for broad generalization.

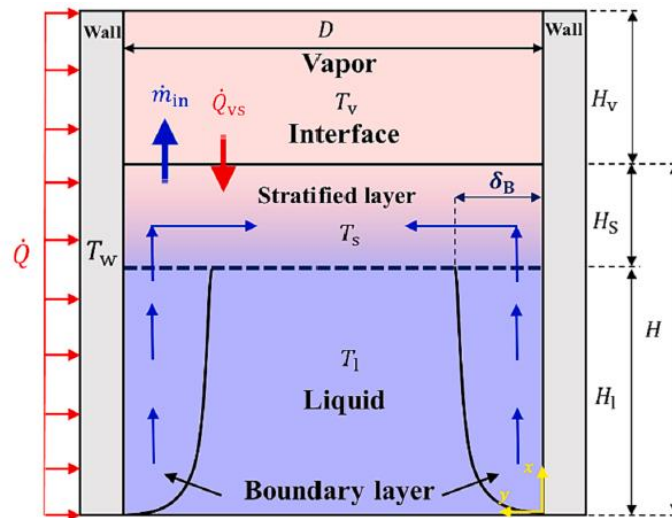


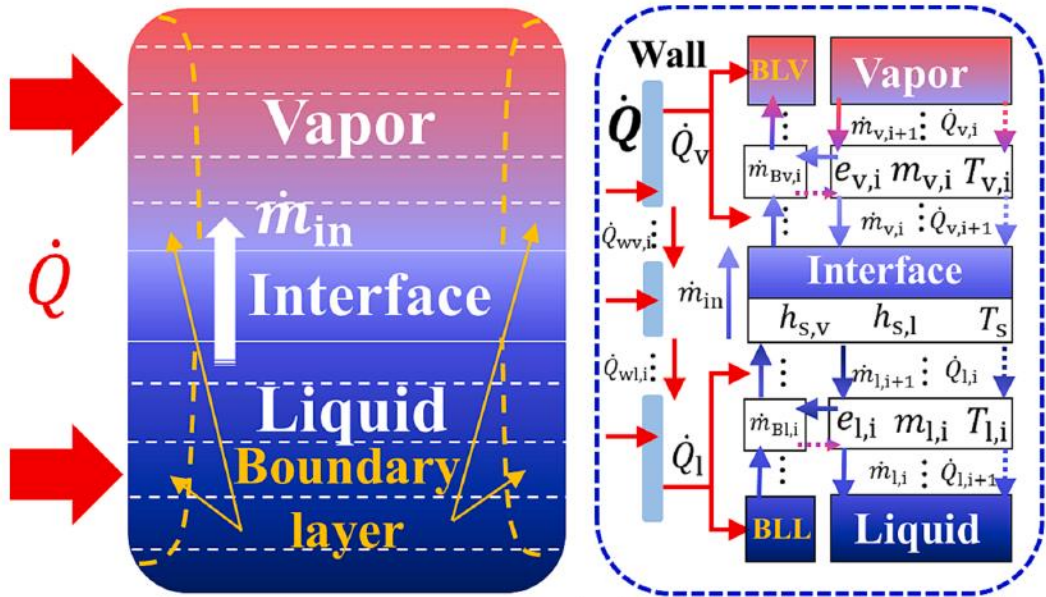
Figure 58: Schematic of the mass and energy exchange in different zones for the TSM [90]

The main assumptions of TSM in a cylindrical tank are listed as follows [90].

- The vapor and liquid are in phase equilibrium.
- The interface and stratified layer are saturated.
- The vapor is superheated and described by the ideal gas equation of state, and the liquid is subcooled and incompressible with a constant temperature.
- The total heat leakage is treated as a uniform heat flux to input.

- The effect of surface tension is neglected.
- **Thermal Multi-Node Model (TMNM)**

The Thermal Multi-Node Model (TMNM) is a more detailed NTEM that divides the computational domain of a cryogenic fluid in a tank, including the same fluid and walls, into multiple nodes. Unlike SEM, TMZM, and TSM, this model discretizes the vapor, liquid, vapor-liquid interface, and boundary layers into finite nodes to solve transient temperature and pressure through mass and energy conservation equations. At the vapor-liquid interface, the volume fraction of each phase remains fixed, and a volume-averaged method is used to describe fluid properties within these interface nodes. The complex structure of the TMNM is graphically represented in [Figure 59](#).



[Figure 59](#): Schematic of the mass and energy exchange in different nodes for the TMNM [90]

As with the TSM, the high level of detail provided by this class of models does not align with the need for generalization. The discretization into multiple nodes, combined with the evaluation of free convection effects, is inherently dependent on the tank's geometry, fluid properties, and operational conditions, drastically limiting its broader applicability.

5.1.2. Review on Existing Studies.

Once an overview of the modelling approaches for cryogenic storage is established, the focus shifts to analysing case studies. The aim of this analysis is to assess the state of the art in terms of applications, particularly in the maritime sector, for different types of stored fluids, and to determine which class of model is used depending on the context. The findings reveal that, in the maritime industry, most studies have concentrated on LNG. Given the well-established LNG market, research has primarily focused on modelling the behaviour of LNG as a tanker's cargo, often considering large storage volumes.

As an example, some of these are reported below to highlight the model class used and its key assumptions.

A first study on the self-pressurization of LNG storage was conducted by Yeon-Pyeong Jo, et Al. [91], focusing on a LNG floating storage regasification unit (FSRU).

The objective was to assess the potential exceedance of the Maximum Allowable Relief Valve Setting (MARVS), which could lead to serious consequences. To address this, a Model Predictive Control (MPC) system is proposed to regulate tank pressure by extracting a portion of the BOG. As a first step, a dynamic model of the LNG storage tank was developed using film evaporation theory at the interface between vapour and liquid. (*Figure 60*). As the authors declare, the assumption of the theoretical vapor–liquid film is important because it can account for the recirculation flow due to the density difference between film liquid and bulk liquid, which has been studied experimentally within this work.

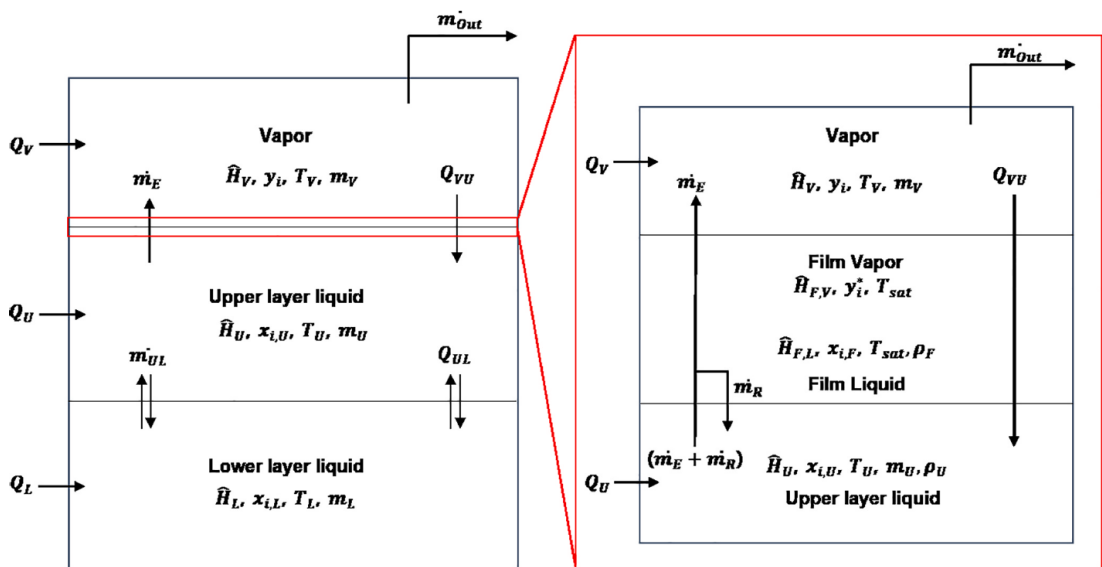


Figure 60: Schematic diagram of LNG tank model and film layer.

In this case, two distinct liquid zones—upper layer liquid and lower layer liquid—are considered due to the varying composition of LNG. This difference leads to stronger stratification and a gradual change in liquid density, as the enhanced evaporation of lighter components affects the overall fluid behaviour.

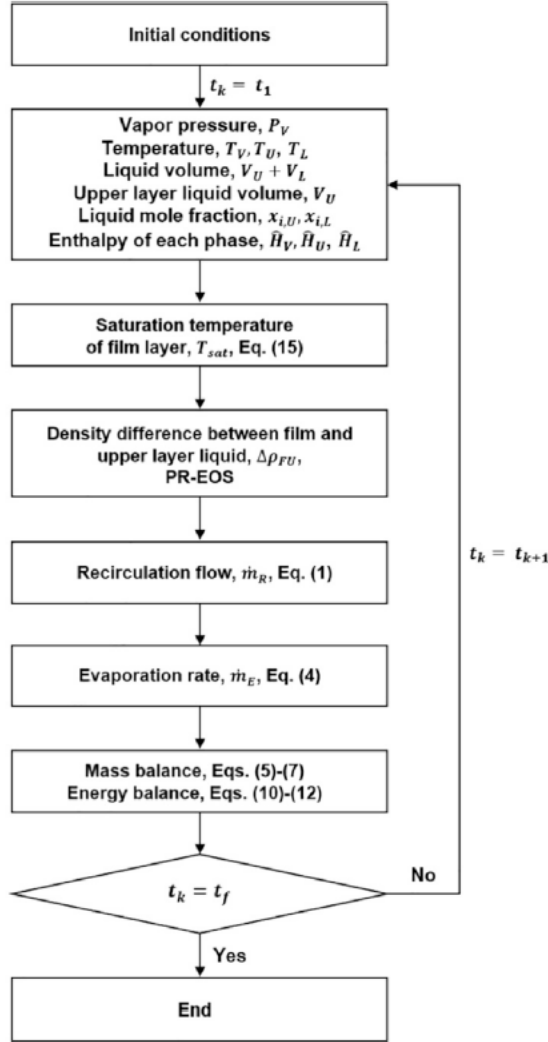


Figure 61: Numerical procedure of the proposed LNG tank model [91]

The approach followed in this study can be classified within the TMZM category, where the Peng-Robinson Equation of State (PR-EOS) has been implemented to determine thermodynamic property variations. This equation is widely used for modelling mixtures of hydrocarbons, such as LNG.

To provide a more detailed overview of the model developed in the initial phase of this study, [Figure 61](#) presents its flow diagram. Additionally, considering initial data resumed in [Table 21](#), [Figure 62](#) reports the model's results for a 4-hour simulation, directly comparing them with experimental data from the literature. The strong agreement between the two highlights the accuracy and potential of the TMZM approach. However, the need for experimental identification of recirculation flows constrains this approach to a specific case study, confirming the limited generalizability of this class of models.

MAIN INPUT	
Tank Volume	44,164 m ³
Initial Pressure	1.1 bar
Initial temperature of upper layer	112.4 K
Initial temperature of lower layer	113.3 K

Table 21: Main input and initial conditions [91]

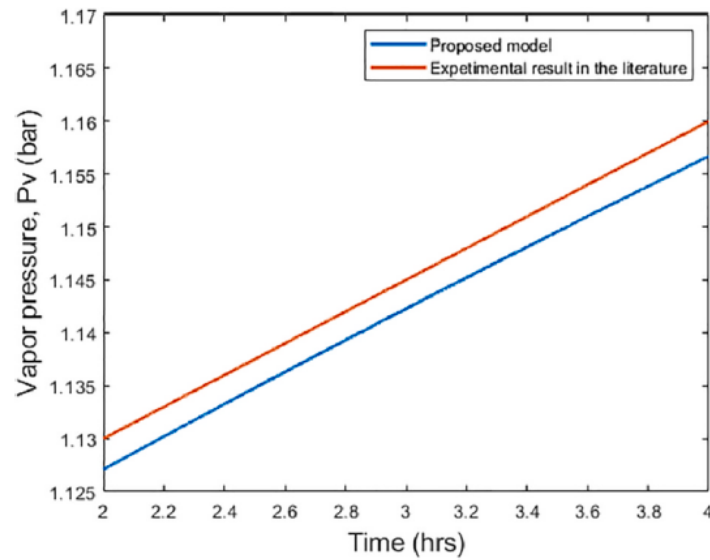


Figure 62: Comparison with the proposed model and experimental data [91]

Regarding the shipping sector, a more recent study by the same author [92] focused on estimating the variation in pressure and temperature inside a LNG carrier storage tank, storing LNG as cargo. This was achieved by conducting a dynamic simulation of the mathematical model for a non-equilibrium LNG tank. Different initial filling ratios (10%, 50%, and 94% by volume) were applied in the modelling and analysis. Furthermore, a sealed condition tank mode and a venting mode have been studied.

The approach is similar to the previous work, as it also involves the separation of the LNG into three distinct zones (lower LNG, upper LNG, and vapor), as shown in [Figure 63](#).

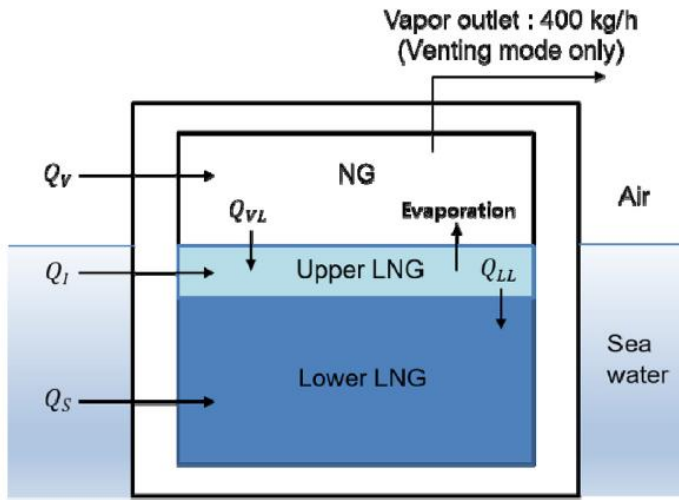


Figure 63: Schematic of the LNG tank [92]

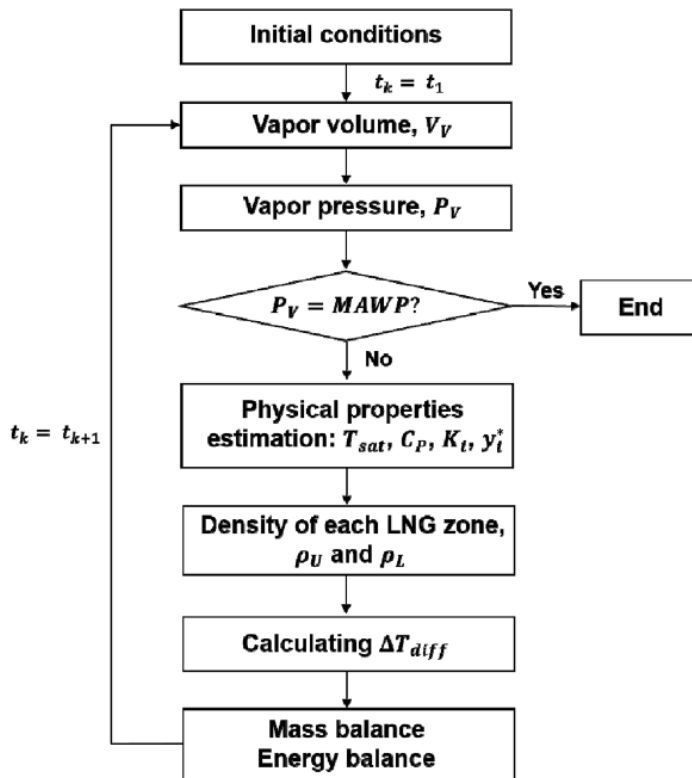


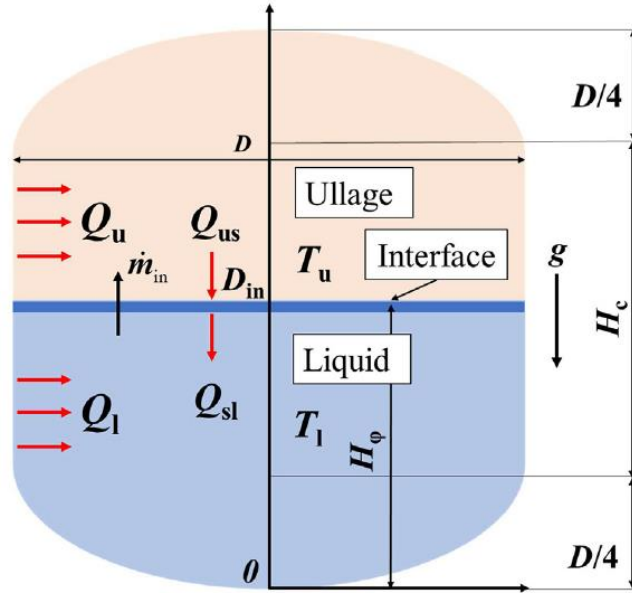
Figure 64: Numerical solution for the proposed LNG tank model [92]

In this case, a layer theory at the interface was not employed; instead, a direct interaction between the upper LNG and the vapor phase was considered. The same approach was applied to model the interaction between the upper and lower LNG zones. However, heat exchange between the different phases is driven by free convective effects, involving convective heat transfer coefficients that are not specified when the interaction between the upper LNG and vapor zone is modelled. The approach used can once again be classified under the TMZM category.

For further clarification of the methodology followed, a flowchart is provided in [Figure 64](#).

Focusing on LH_2 , different studies are available in the literature primarily addressing self-pressurization under sealed conditions. The main field of application for this type of cryogenic hydrogen storage is aerospace, as this sector has shown the greatest interest in LH_2 to date.

As an example, H.R. Wang et Al. [93] developed a model for predicting self-pressurization in a NASA multi-purpose hydrogen test bed tank. The approach used for this application falls within the TMZM model class. This method distinguishes between the liquid and vapor phases, yielding quite precise results, as previously highlighted for LNG, when simulated outcomes are compared with experimental data. Specifically, for this application, a layer theory at the interface was applied, meaning that the evaporation mass flow is derived from the energy balance at the interface. The multi-purpose hydrogen test bed approach is simplified in [Figure 65](#).



[Figure 65](#): Computational domain of TMZM for the Multi-purpose hydrogen test bed [93]

Similarly, for this case study, the authors emphasize that the convective heat transfer coefficients used to evaluate the heat exchange between the vapor phase-interface and the interface-liquid phase are defined using modified factors of heat transfer, experimentally determined for the specific case study. This confirms the limitations of using this type of model when generalization is required.

For completeness, the flowchart of the model studied is presented in [Figure 66](#).

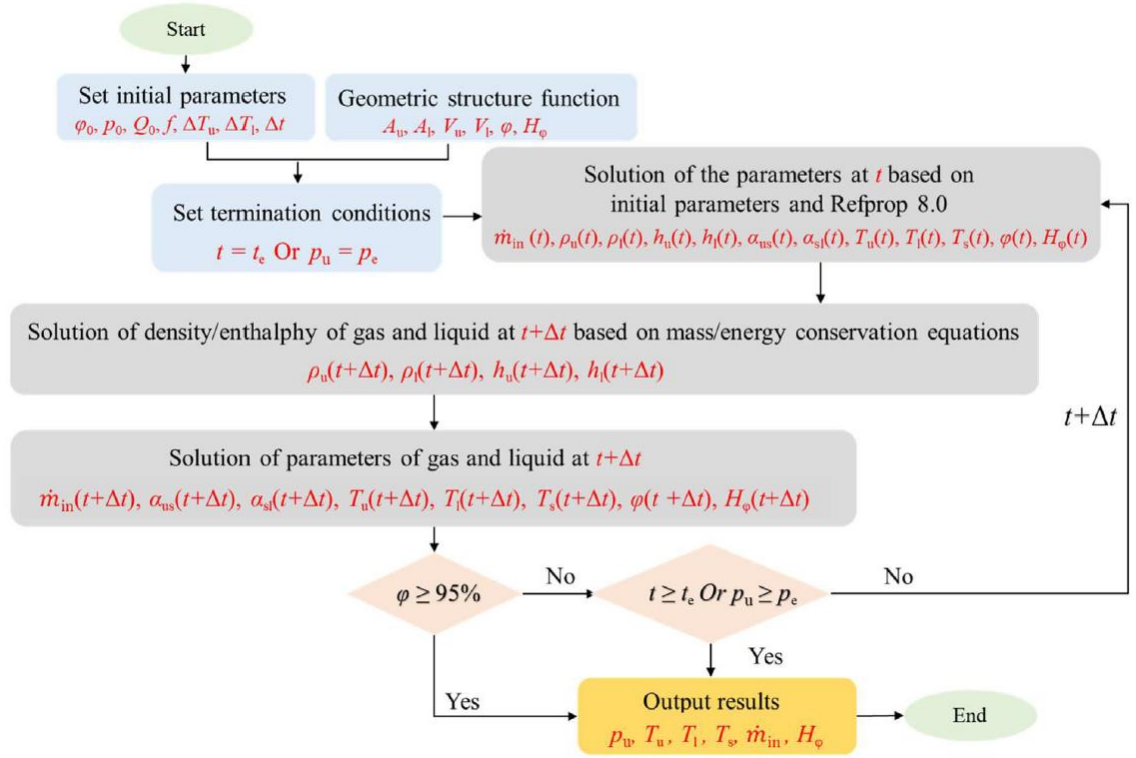


Figure 66: Flow chart of TMZM solution process [93]

From the same study, which focused on an existing tested LH₂ tank, results on self-pressurization using different model classes are presented in [Figure 67](#). Specifically, the pressure build-up representation considers varying initial fill levels, heat leakages, and starting pressures, reported in [Table 22](#). Furthermore, trends represented by experimental results are compared with the model outcomes. As can be observed, the TMZM class achieves excellent accuracy in predictions, satisfactorily matching experimental data. In contrast, thermal homogeneous models (SHM) exhibit significant deviation from the experimental data. A better match is achieved by applying the corrections suggested by the MTHM, identified for LH₂.

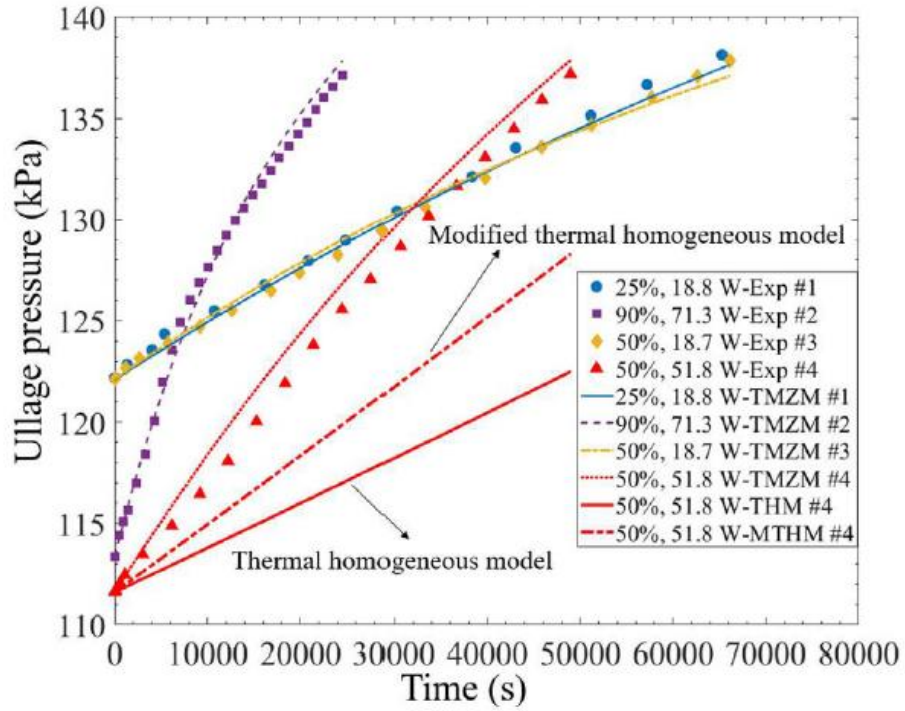


Figure 67: Comparison of pressure curves between three models against the experiments [93]

Number	φ_0	Initial Pressure (KPa)	Terminated Pressure (kPa)	Holding time (s)	Q_{tot} (W)
#1	25%	122.1	137.8	66,100	18.8
#2	90%	113.3	137.1	24,560	71.3
#3	50%	122.1	137.8	66,115	18.7
#4	50%	111.6	137.2	48,970	51.8

Table 22: Initial data and experimental results of the multi-purpose hydrogen test bed tank [93]

This study highlights that the majority of models available in the literature are highly detailed and can be applied to specific case studies, due to the challenging nature of defining the convective heat transfer coefficients. These models belong to a class characterized by a level of detail greater than that of TEM.

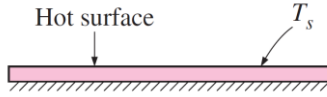
Furthermore, while several studies are present in literature for LNG and LH₂, a NH₃ modelling lack has been found.

5.2. Description of the Dynamic Model.

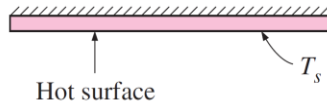
Following the literature analysis, which highlights the main features of different classes of models for cryogenic storage simulation, it was concluded that NTEM does not align with the objectives of this study. For these purposes, it was determined that the most suitable category of model was SHM.

This approach offers a reduced level of detail while allowing for easy generalization, making it well-suited for modelling thermodynamic behaviour under real operating conditions. This choice was made because the use of more detailed models, distinguishing between the liquid and vapor phases—and consequently simulating the heat exchange between the two through the interface—would require the evaluation of convective heat transfer coefficients between the liquid and gas in a proper manner.

In this context, convective heat exchange is not described through coefficients identified via general correlations. The most comparable scenario, represented by a flat plate—for which the relevant equations are provided in (6), (7), (8), and (9)—does not realistically capture the situation due to the inability of the fluid to bypass the solid boundary modelled by the interface [94] ([Figure 68](#)).



$$\begin{aligned} Ra &\in [10^4; 10^7] & Nu &= 0.54 \cdot Ra^{1/4} \\ Ra &\in [10^7; 10^{11}] & Nu &= 0.15 \cdot Ra^{1/3} \end{aligned} \quad (6)$$



$$Ra \in [10^5; 10^{11}] \quad Nu = 0.27 \cdot Ra^{1/4} \quad (7)$$

$$Ra = Gr \cdot Pr = \frac{g \cdot (T_{sat} - T_{\infty}) \cdot (A_s/P_s)^3}{\nu \cdot \alpha} \quad (8)$$

$$Nu = \frac{h \cdot (A_s/P_s)}{k} \quad (9)$$

Where:

- Ra = Raleigh number
- Nu = Nusselt number

- Gr = Grashof number
- Pr = Prandtl number
- g = Gravity acceleration
- T_{sat} = Saturation temperature
- T_{∞} = Temperature at an infinite distance from the surface
- A_S = Vapour-liquid interface area
- P_S = Vapour-liquid interface perimeter
- h = Convective heat transfer coefficient
- k = Conductive heat transfer coefficient

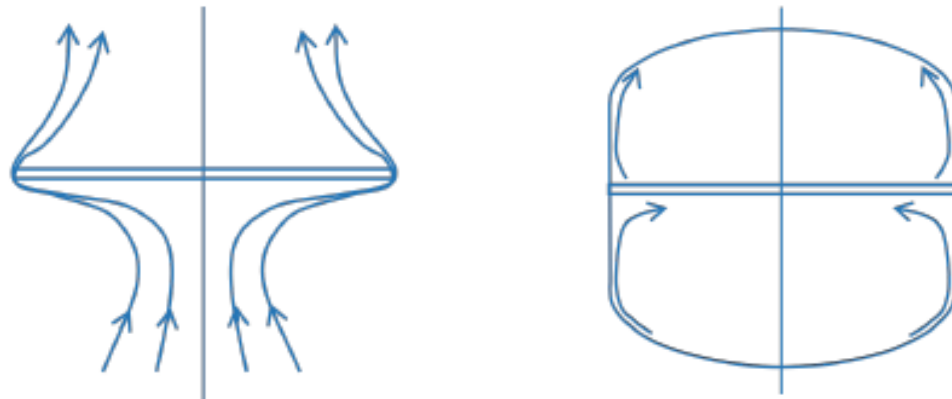


Figure 68: Highlighting of the differences between the horizontal heated downward-facing plate model and the liquid-ullage interface in a finite volume tank.

As a result, to enable the development of a preliminary calculation model applicable on a large scale, it was deemed necessary to decoupling the problem from the geometric characteristics of the storage system, both in terms of shape and size. This requirement consequently ruled out the possibility of implementing a model that accounts for heat exchange between the liquid and gas phases.

Another requirement was the ability to simulate a potential emptying process, achieved by extracting a liquid mass flow rate corresponding to the amount required by the engines under specific load profiles. Under these conditions, the convective motions that could have developed in a sealed tank would have been inevitably disrupted by this scenario, compromising the accuracy of the evaluation.

Finally, the application context presented an additional limitation for the use of more detailed models. Being on board a ship, the induced movements within the stored fuel cannot be overlooked. Due to the ship's motions (rolling, pitching, etc.), the presence of a liquid interface leads to the phenomenon of sloshing, which generates macroscopic motions on the liquid free surface through the wave formation. This phenomenon affects the accuracy of thermal exchange evaluations between the liquid and vapor, mainly due to two factors. The first concerns the alteration of the interface between the two phases, which is no longer flat; instead, due to the three-dimensional nature of wave motion, the heat exchange surface area increases. The second reason is directly attributable to the liquid movements, which inevitably affects natural convection and, consequently, the definition of the related coefficients.

For these reasons, it was deemed that a TMZM model was not suitable for modelling the thermodynamic evolution of the stored fuel.

Therefore, an SHM model considering the possibility of simulating mass flow rate extraction and a BOG processing scenario, as shown in [Figure 69](#), has been developed in a Python environment. Specifically, regarding the BOG management system, a reliquification system that extracts vapor and reintroduces liquid has been considered.

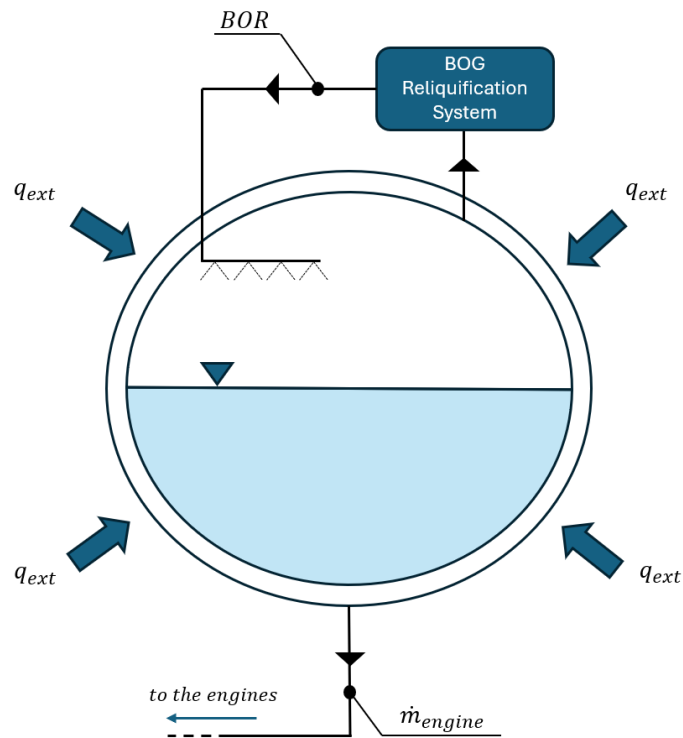


Figure 69: Schematic of the SHM model, considering engine mass flow and BOG processing.

To better understand the mathematical process describing the progression of thermodynamic features, the model's flow diagram is shown in [Figure 70](#). The main assumption was that the thermodynamic process is represented by a progression of equilibrium states at saturation conditions, as required by this class of model. Furthermore, homogeneous temperature within the tank has been considered.

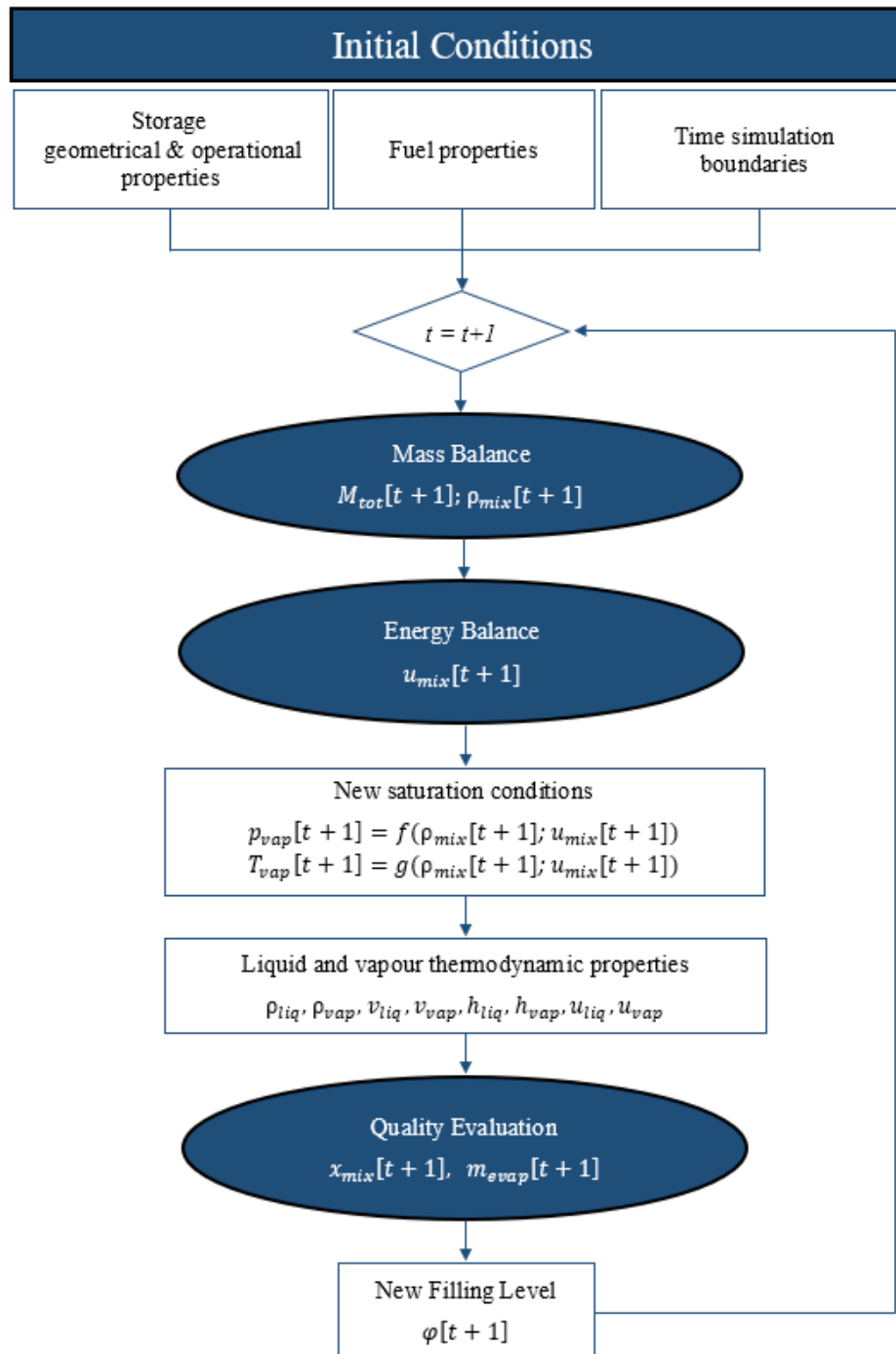


Figure 70: Saturated Homogeneous Model (SHM) flow chart

For this type of model the variation in thermodynamic properties can be determined based on averaged quantities of the liquid-gas mixture within the storage system. In particular, since the evaporated mass cannot be directly measured—unlike models that apply layer theory at the liquid-vapour interface—it can instead be inferred from changes in the mixture's quality, following the attainment of new internal energy conditions. For this reason, evaluating the quality is essential for predicting the evolution of the liquid and vapour masses inside the tank.

With this approach, once the initial conditions are defined, the physics of the storage is described by the mass balance equations, represented by (10), (11) and (12), respectively for the liquid, the vapor and in global terms, as well as by the energy balance equation, identified by (13).

$$\frac{dM_{liq}(t)}{dt} = -\dot{m}_{evap}(t) - \dot{m}_{engine}(t) \quad (10)$$

$$\frac{dM_{vap}(t)}{dt} = \dot{m}_{evap}(t) \quad (11)$$

$$\frac{dM_{tot}(t)}{dt} = -\dot{m}_{engine}(t) \quad (12)$$

Where:

- M_{liq} = Liquid mass within the storage tank
- $\dot{m}_{evap}$ = Evaporated mass flow
- $\dot{m}_{engine}$ = Mass flow required from the engines
- M_{vap} = Vapour mass within the storage tank
- $M_{tot} = M_l + M_v$ = Total mass within the storage tank

$$\frac{d(u_{mix}(t) \cdot M_{tot}(t))}{dt} = \dot{q}_{ext}(t) - h_{liq}(t) \cdot \dot{m}_{engine}(t) - BOR(t) \cdot [h_{vap}(t) - h_{liq}(t)] \quad (13)$$

Where:

- u_{mix} = Specific internal energy of the mixture (liquid + vapour) within the storage tank
- $\dot{q}_{ext}$ = Heat flow entering from the external environment
- h_{vap} = Specific enthalpy of the vapour
- h_{liq} = Specific enthalpy of the liquid
- BOR = Boil-off rate representing the vapour mass flow that need to be processed

In equation (13), the heat flow entering inside the tank need to be defined. This quantity depends directly on the tank's properties and on both the external and internal temperatures. The following assumptions have been made for evaluating $\dot{q}_{ext}(t)$:

1. The model considers only pure conduction, neglecting convective effects near both the inner and outer tank walls.
2. Only the insulation and its conductive heat coefficient are taken into account, as the high thermal conductivity of the metallic layers is assumed negligible.

These two assumptions are illustrated in [Figure 71](#), representing the tank wall and comparing the assumed condition (simplified case) with a more realistic representation.

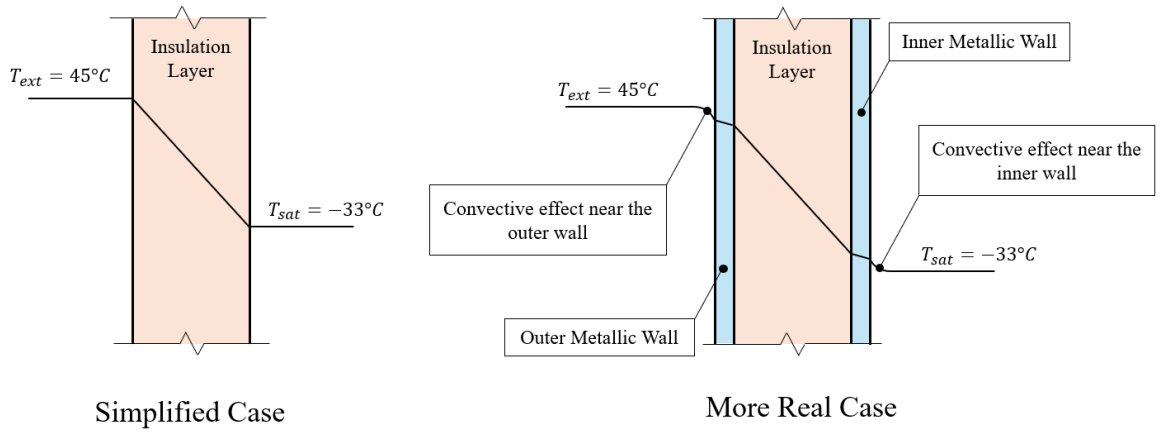


Figure 71: Simplified and more realistic modelling of the tank wall.

Based on this hypothesis, $\dot{q}_{ext}(t)$ is defined as shown in Equation (14).

$$\dot{q}_{ext}(t) = \frac{S_{tank} \cdot (T_{ext} - T_{sat}(t)) \cdot k_{ins}}{th_{ins}} \quad (14)$$

Where:

- S_{tank} = External surface of the tank
- T_{ext} = Temperature of the external surrounding environment
- T_{sat} = Saturation temperature within the storage tank
- k_{ins} = Conductive heat coefficient of the insulation

- th_{ins} = Thickness of the insulation

The last term in Equation (13) represents the effect of BOG processing. The BOR is evaluated as the vapor mass flow required to maintain the pressure within the tank below the MARVS limit. The main assumption considered is the use of a reliquefaction system as the BOG management plant. This process involves extracting a portion of the vapor, reliquefying it, and reintroducing the same mass flow into the tank as liquid. Considering the storage system as a control volume, this process is energetically described by the extraction of energy through the removed vapor mass and the subsequent reintroduction of an energy content via the same mass flow in liquid phase. Therefore, previous contributions are characterized by vapor and liquid enthalpy, respectively. Specifically, if the evaporated mass—not due to liquid extraction—is processed, representing the BOR, it is possible to maintain stable thermodynamic conditions at the set threshold. Regarding the mass balance, considering the reintroduction of the extracted mass, no changes have been made. The BOR estimation is represented in (15).

$$BOR(t) = \frac{\dot{q}_{ext}(t) - \dot{v}_{engine}(t) \cdot h_{vap}(t)}{h_{vap}(t) - h_{liq}(t)} \quad (15)$$

The assessment of the variation in the specific internal energy of the mixture $\left(\frac{du_{mix}(t)}{dt}\right)$, considered as an average quantity within the storage, allows for the determination of the system's new thermodynamic properties. In particular, for this type of model, which provides global information without a strict distinction between liquid and vapour, the specific volume and density of the mixture need to be evaluated, as reported in (16).

$$v_{mix}(t) = \frac{V_{tot}}{M_{tot}(t)} = \frac{1}{\rho_{mix}(t)} \quad (16)$$

Knowing $v_{mix}(t)$ and $u_{mix}(t)$ at the current timestep, the thermodynamic conditions inside the tank are identified. Therefore, the corresponding saturation pressure and temperature can be evaluated. In this case REFPROP software (Reference Fluid Thermodynamic and Transport Properties), developed by the National Institute of Standards and Technology (NIST) was used for identifying these two quantities as a function of $\rho_{mix}(t)$ and $u_{mix}(t)$ (17).

$$\begin{aligned} p_{sat}(t) &= f(\rho_{mix}(t), u_{mix}(t)) \\ T_{sat}(t) &= f(\rho_{mix}(t), u_{mix}(t)) \end{aligned} \quad (17)$$

Other thermodynamic properties for both the liquid and vapour phases can be evaluated using the same REFPROP database. This distinction between two phases, is crucial for determining the variation in quality $x(t)$. As stated in (18), knowing $p_{sat}(t)$ and $T_{sat}(t)$, these values serve as the primary inputs for the subsequent evaluation. Since they correspond to saturation conditions, they are not independent but bi-univocally paired. Therefore, only one of them, either $p_{sat}(t)$ or $T_{sat}(t)$, can be chosen as an input.

To differentiate between the two phases, the second input can be the quality (x^*). This variable does not represent the actual quality inside the storage tank but serves as a dummy value. Specifically, it is used as a secondary input to distinguish the liquid phase ($x_{liq}^* = 0$) from the vapour phase ($x_{vap}^* = 1$) when REFPROP is employed to determine the thermodynamic properties of both phases, as indicated in (18).

$$\begin{aligned} v_{liq}(t) &= (\rho_{liq}(t))^{-1} = f(p_{sat}(t), x_{liq}^*) \\ v_{vap}(t) &= (\rho_{vap}(t))^{-1} = f(p_{sat}(t), x_{vap}^*) \end{aligned} \quad (18)$$

Similarly, the thermodynamic properties listed in (19) are defined to track their evolution over time.

$$h_{liq}(t), h_{vap}(t), u_{liq}(t), u_{vap}(t) \quad (19)$$

The final value to be determined is the updated quality of the mixture inside the storage tank, which can be evaluated using either specific volumes or specific internal energies, as in (20).

$$x(t) = \frac{v_{mix}(t) - v_{liq}(t)}{v_{vap}(t) - v_{liq}(t)} = \frac{u_{mix}(t) - u_{liq}(t)}{u_{vap}(t) - u_{liq}(t)} = \frac{M_{vap}(t)}{M_{tot}(t)} \quad (20)$$

Since $x(t)$ is defined as the ratio between the vapour mass and the total mass, its variation between two timesteps represents the evaporated mass, as shown in (21). In this case, the total mass is already reduced by the mass flow rate and is therefore treated as an updated constant.

$$\dot{m}_{evap}(t) = M_{tot} \cdot \frac{dx(t)}{dt} = \frac{dM_{vap}(t)}{dt} \quad (21)$$

To validate the predicted results of the model, a preliminary analysis was conducted performing a quality mapping as a function of temperature, considering different filling levels. This assessment is useful to predict the recurrence of evaporation or condensation based on the temperature reached

inside the tank. Specifically, results obtained by the quality mapping, have been compared with similar analysis present in literature for SHM. **Figure 72**, extracted by Wang et al. [90], illustrates the behaviour of LH₂ iso-quality curves on a diagram where the saturation temperature (T_s) is plotted on the x-axis, and the average specific volume—representative of the initial filling level—is plotted on the y-axis, under sealed conditions. Additionally, the figure includes the boundary curve $\frac{dx}{dT_s} = 0$ which demarcates the evaporation zone ($\frac{dx}{dT_s} > 0$) from the condensation zone ($\frac{dx}{dT_s} < 0$).

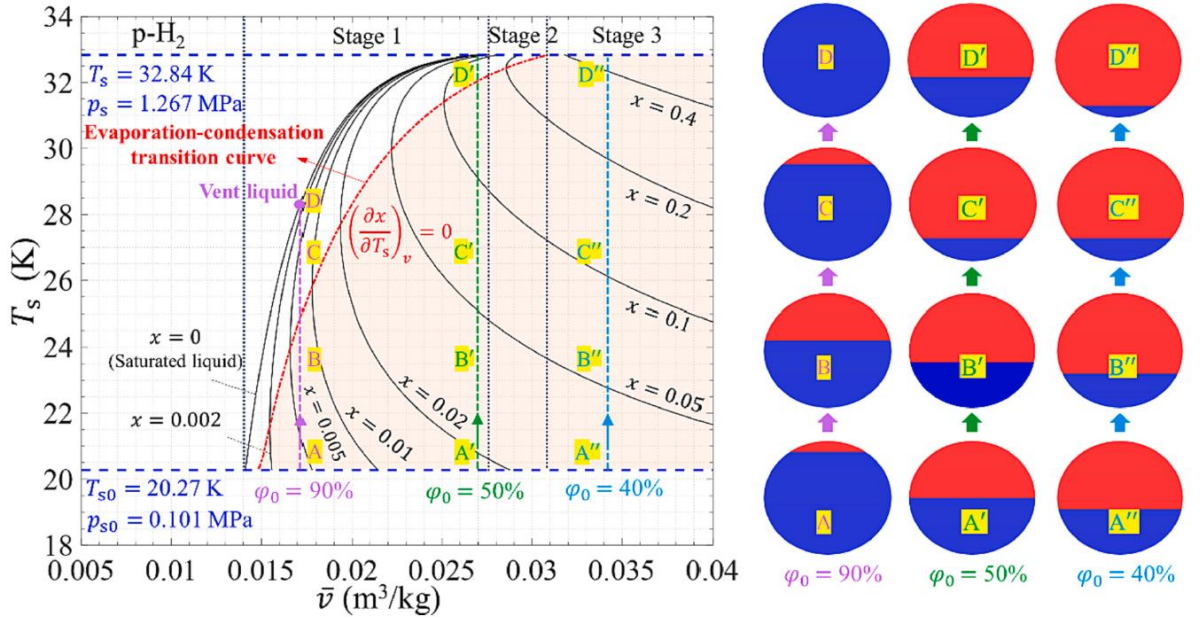


Figure 72: Schematic of the thermal process of the self-pressurization in LH₂ tanks based on the SHM

Following the indications reported in **Figure 72**, it is possible to distinguish between evaporation and condensation conditions. Therefore, the model has been run under sealed conditions to verify whether the same behaviour occurs, considering initial filling and saturation temperature as leading variables.

The choice of hydrogen as the stored fluid for this validation was primarily driven by its wider availability in dedicated studies compared to NH₃. Furthermore hydrogen can be treated as a pure substance in a manner analogous to NH₃, eliminating potential inconsistencies arising from the varying compositions of mixtures such as LNG. In the case of LNG, the presence of multiple chemical components would complicate thermodynamic calculations and could lead to stratification effects due to density differences, as well as evaporation predominantly driven by the more volatile components.

Therefore, parahydrogen, whose concentration is about 95% under these thermodynamic conditions, has been chosen as stored liquid for conducting the model validation. In this context an initial temperature of 21 K and a corresponding saturation pressure of approximately 124,960 Pa have been considered as starting point. A reduced tank volume of 10 m³ was used, with a constant heat leak of 80W. Under these conditions, simulations were performed, mapping both quality and evaporated mass flow as functions of temperature, up to the hydrogen critical point. ($p_C \approx 1.293$ MPa ; $T_C \approx 33.2$ K). Several sample initial filling levels were used as initial conditions.

From [Figure 73](#), presenting the mapping results, it can be observed that the hydrogen quality for filling levels up to approximately 45% is characterized by increasing curves across the entire temperature range under consideration. ($\frac{dx}{dT_s} > 0$). This indicates that the vapor mass continues to increase, describing an evaporation condition.

Beyond the 45% as initial filling, the quality curves exhibit a maximum point, distinguishing between a rising trend ($\frac{dx}{dT_s} > 0$) and a decreasing one ($\frac{dx}{dT_s} < 0$). Therefore, evaporation occurs in the rising part of the curve, while a decrease in quality—and consequently in vapor mass—characterizes a condensation scenario. This phenomenon is driven by the thermodynamic conditions established within the storage system, taking into account various saturation states, uniquely described by the different temperature-pressure pairs. As it is possible to observe in [Figure 73](#), the maxima of the quality curves are defined by $\frac{dx}{dT_s} = 0$. By connecting these different maxima, the resulting curve represents the boundary distinguishing between evaporation and condensation zones.

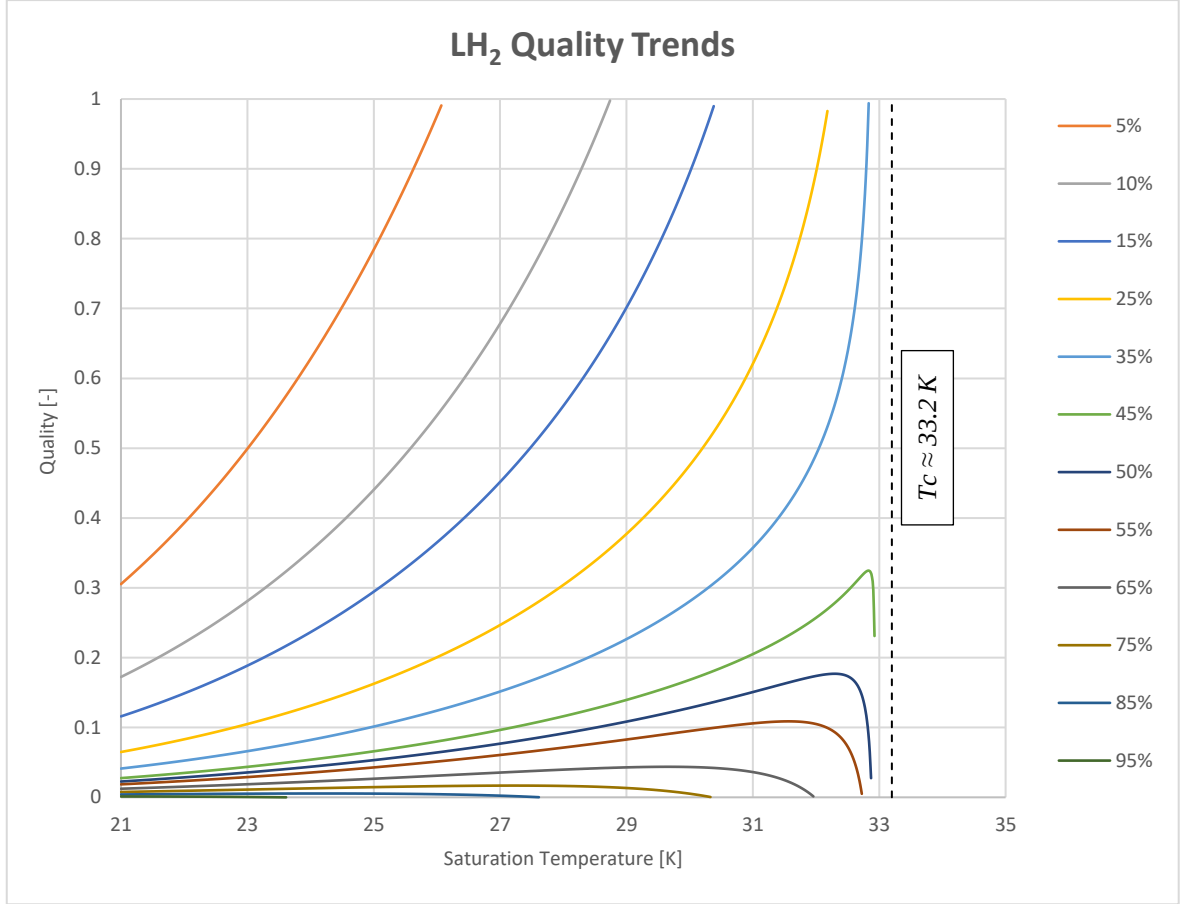


Figure 73: LH₂ quality trends for different initial fillings

In line with the aforementioned observations, **Figure 74** illustrates the trends of evaporated masses as a function of saturation temperature across various filling levels. Condensation occurs where the evaporated mass takes on values less than zero. Similar to the previous case, this phenomenon is observed only for filling levels exceeding approximately 45%. The temperatures at which the transition from an evaporation to a condensation condition occurs, for the different filling levels, correspond to the maximum points on the quality curves.

As can be observed from **Figure 74**, evaporation curves for initial filling levels of 5%, 15%, and 25% are interrupted. This happens because, at the breakpoint, the quality reaches unity, leading to the depletion of the liquid phase. Similarly, the curves for initial fillings of 65%, 75%, 85%, and 95%, due to condensation, are broken because the tank becomes completely filled with liquid, reducing the quality to zero. The conditions $x = 1$ and $x = 0$ are considered as limits, and once these are reached, the simulation is terminated. This decision was made because the previously set limit values do not reflect the actual operating conditions in the specific application field of the model.

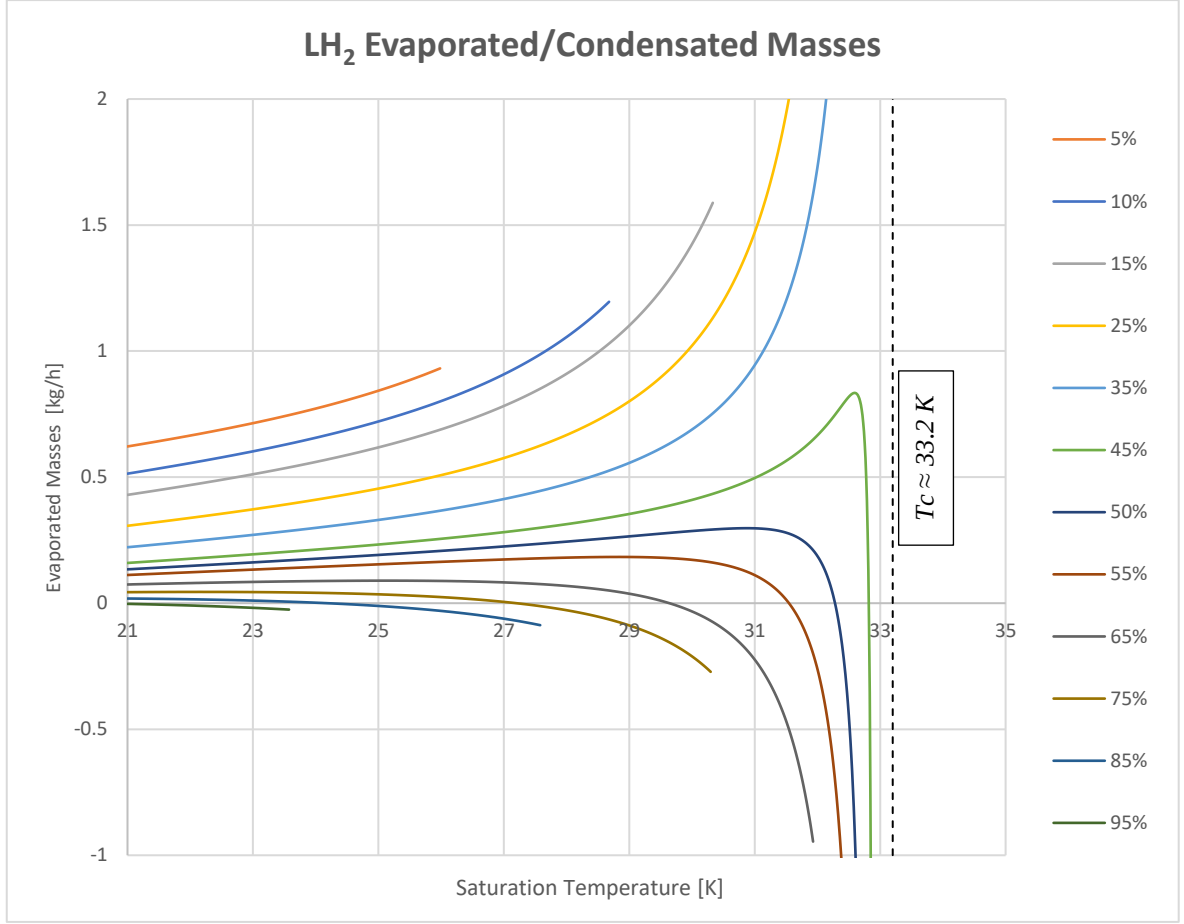


Figure 74: LH₂ evaporated/condensed masses for different initial fillings

As a mapping results, considering an initial filling level of 50% as a sample, it can be observed from [Figure 73](#) that the curve $\frac{dx}{dT_s} = 0$ is crossed at a saturation temperature of 32.29 K, indicating the onset of condensation over this temperature. This behaviour is consistent with [Figure 72](#), which shows that for a 50% initial filling level, condensation begins to occur at around 32 K.

Considering the same storage characteristics as before, ($V_{int} = 10m^3$ and $Q = 80W$), [Figure 75](#) presents a comparative analysis of the liquid and vapor masses and volumes inside the tank throughout the simulation. These variables are now represented as functions of time, nonetheless indicating an increase in temperature due to the heat entering from the outside. The study examines initial filling levels of 5%, 25%, 50%, 75%, and 95% as representative cases, all under sealed conditions. It is important to note that the initial filling levels and their variation over time are linked to the filling volume, which does not necessarily follow the same trend as the mass.

As can be observed for lower initial filling levels (5% and 25%), the liquid mass decreases monotonically due to evaporation. According to [Figure 74](#), these initial conditions lead to a

progression of thermodynamic states, allowing only evaporation until the complete depletion of the liquid. The liquid volume follows the same decreasing trend as the mass in these cases, ultimately reaching zero for the liquid phase. This process results in a reduction in the filling level and an increase in the quality, which reaches unity once the liquid is entirely depleted.

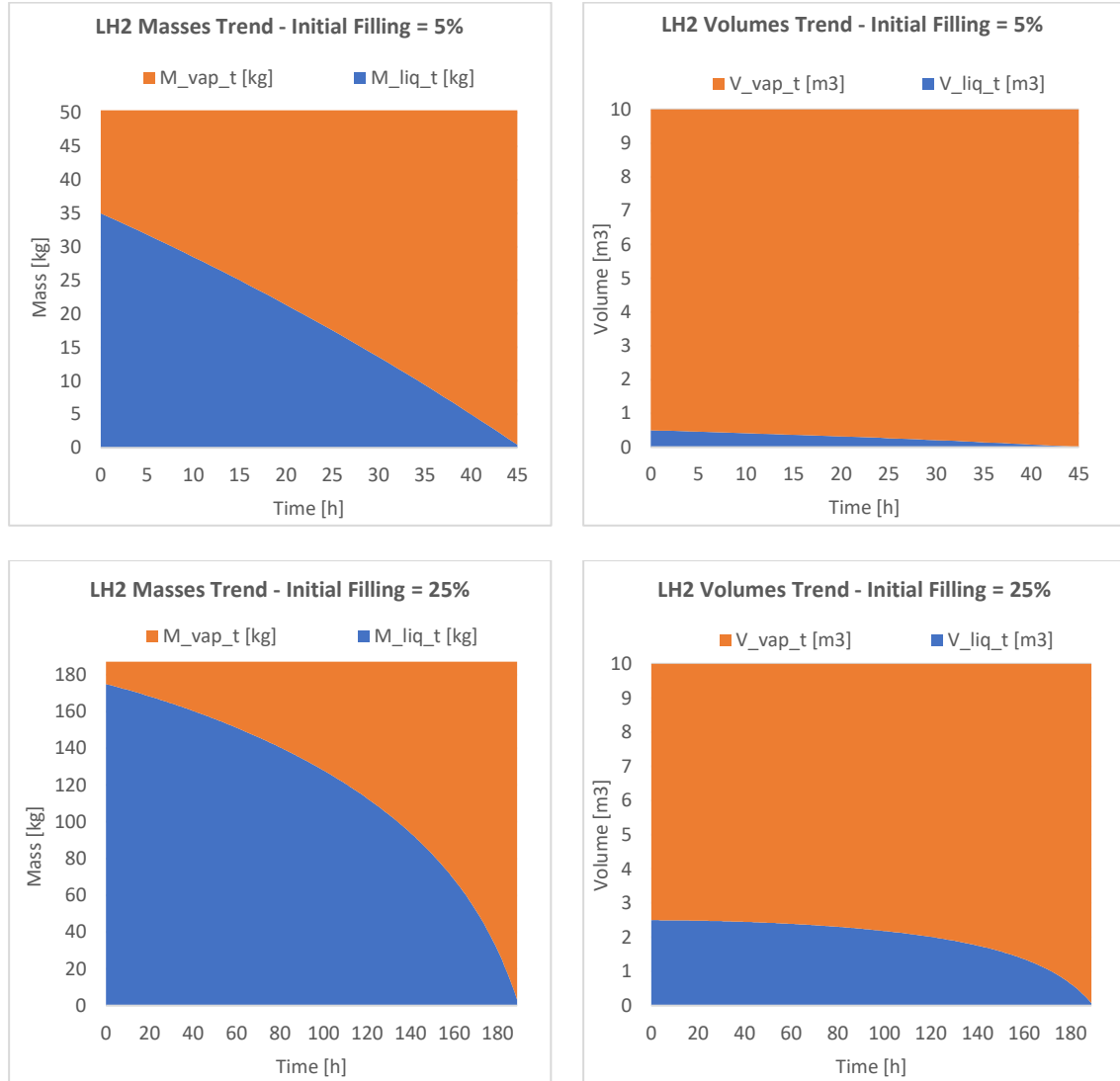


Figure 75: Progressions of liquid and vapor mass and volume throughout the simulation within the 10 m³ LH₂ plenum for initial fillings of 5% and 25%

In contrast to what was observed in previous case studies, as highlighted in [Figure 76](#), 50% and 75% as initial fillings are characterized by an evaporation zone until the temperature reaches the value corresponding to the maximum quality (or until the evaporation mass flow is zero). At these points, the minimum liquid level is reached. Specifically, this temperature is 32.29 K for the lower initial filling and 27.2 K for the higher one, achieved after 248 hours and 142 hours, respectively. Beyond

this point, for both conditions, condensation occurs more rapidly than the preceding evaporation, resulting in the complete filling of the plenum. This behaviour is similarly observed in [Figure 73](#) and [Figure 74](#).

Regarding the liquid volume trend, it shows a monotonically increasing behaviour over time, which contrasts with the progression of liquid mass. As a result, this leads to a scenario where the liquid mass decreases while the liquid volume — and consequently the filling level — increases.

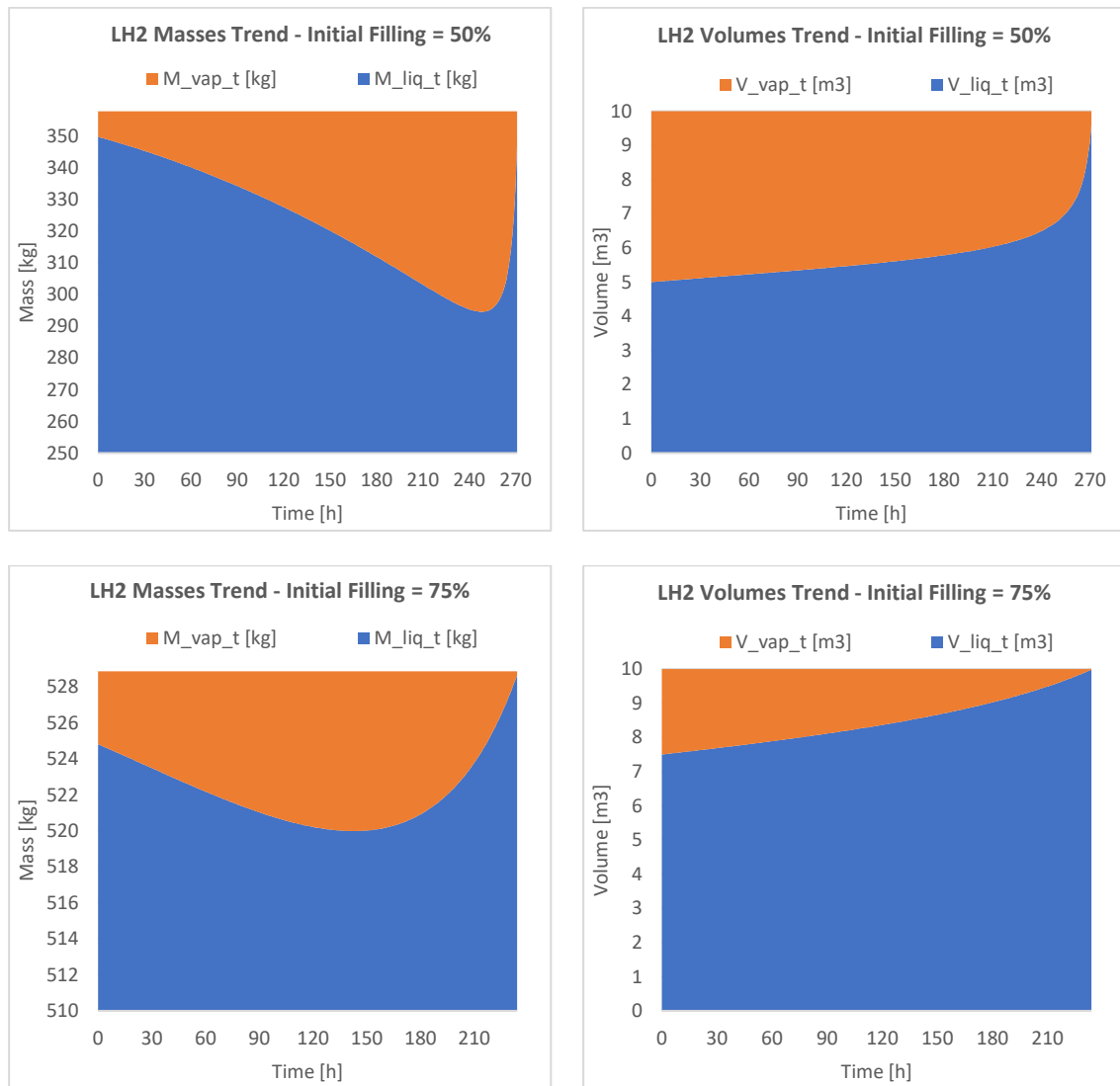


Figure 76: Progressions of liquid and vapor mass and volume throughout the simulation within the 10 m³ LH2 plenum for initial fillings of 50% and 75%

This is due to the progressions over time of the liquid mass and the liquid specific volume, as these quantities are involved in the definition of liquid volume, as shown in (22).

$$V_{liq}(t) = \frac{M_{liq}(t)}{\rho_{liq}(t)} = M_{liq}(t) \cdot v_{liq}(t) \quad (22)$$

Moving through successive equilibrium states, characterized by different saturation conditions, temperature governs the variation of liquid density over time, outweighing the effect of pressure. Therefore, an increase in saturation pressure and temperature leads to an increasing trend in liquid specific volume. *Figure 77* illustrates this behaviour as a function of temperature, remaining unchanged across different initial conditions.

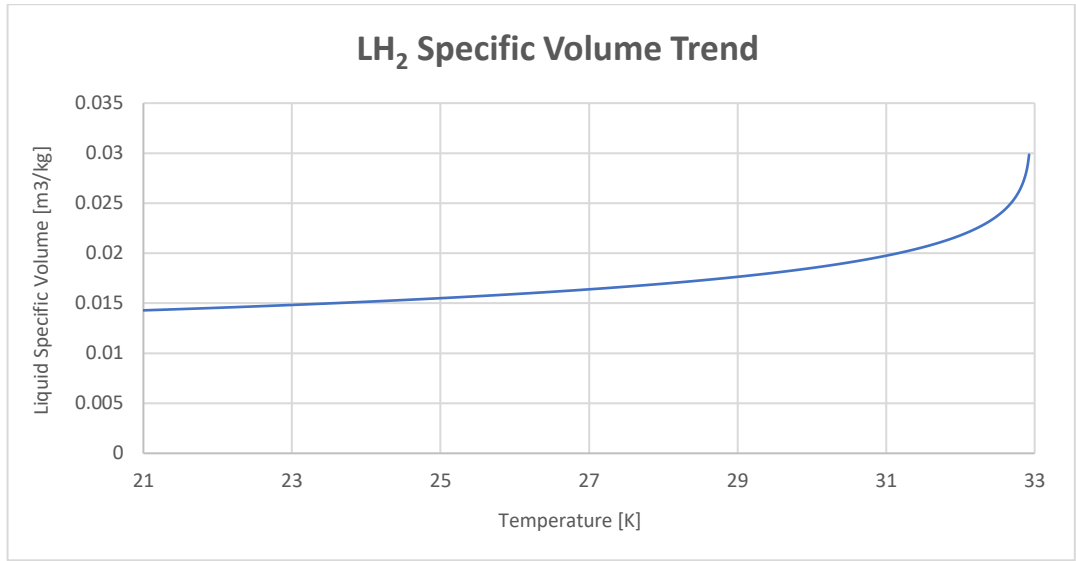


Figure 77: Liquid specific volume trend across different saturation conditions, represented by saturation temperatures

Therefore, a comparison between specific volume and liquid mass has been conducted. Specifically, both quantities were normalized based on their initial values to align them on a common scale. From *Figure 78*, which shows the normalized trends of liquid mass ($\bar{M}_{liq}$) and specific volume ($\bar{v}_{liq}$) for the indicated initial fillings, it is evident that, for an initial filling of 50%, the specific volume increases more rapidly over time compared to the decrease in the normalized liquid mass, realizing the condition expressed in (23).

$$\left| \frac{d\bar{M}_{liq}(t)}{dt} \right| < \left| \frac{d\bar{v}_{liq}(t)}{dt} \right| \quad \forall t \in [0, t_{end}] \quad (23)$$

Consequently, when $M_{liq}(t)$ and $v_{liq}(t)$ are multiplied, the resulting function, representing the liquid volume, increases monotonically throughout the entire simulation range $\left(\frac{dV_{liq}(t)}{dt} > 0 \forall t \in [0, t_{end}] \right)$, thereby explaining this counterintuitive behaviour between liquid mass and volume.

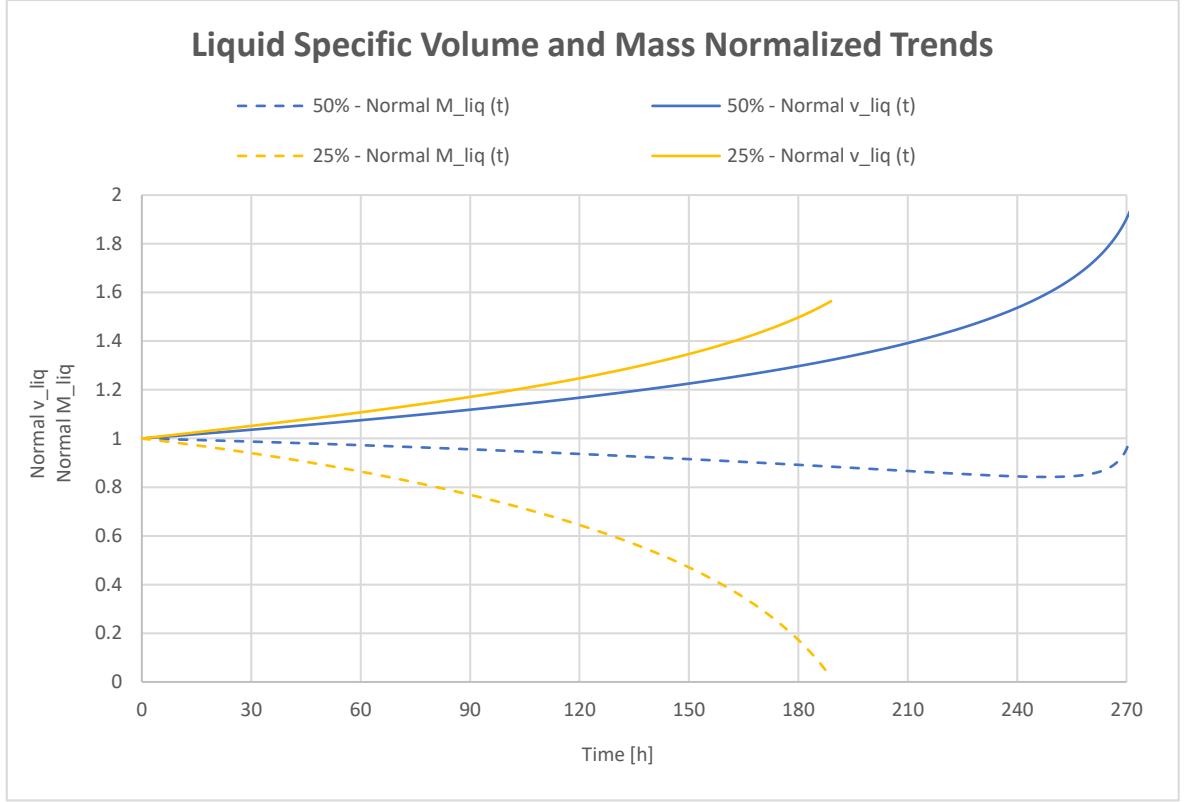


Figure 78: Normalized trends for specific volume and liquid mass throughout the simulation

Conversely, from the same [Figure 78](#), if an initial filling of 25% is considered, the normalized liquid mass decreases more rapidly than the normalized specific volume increases over time, realizing condition represented in (24).

$$\left| \frac{d\bar{M}_{liq}(t)}{dt} \right| > \left| \frac{d\bar{v}_{liq}(t)}{dt} \right| \quad \forall t \in [0, t_{end}] \quad (24)$$

Consistently with [Figure 75](#), both the liquid volume and the filling trends decrease, leading to liquid depletion $\left(\frac{dv_{liq}(t)}{dt} < 0 \quad \forall t \in [0, t_{end}] \right)$.

Following the same physical principles previously described, the study with the highest initial filling level (95%), shown in [Figure 79](#), highlights a further different behaviour. In this case, as it can be inferred by [Figure 73](#) and [Figure 74](#), only condensation occurs. Therefore, the simulation presents a monotonically increasing trend for both the liquid mass and volume, until the plenum is completely filled. This conditions is reached after approximately 64 hours.

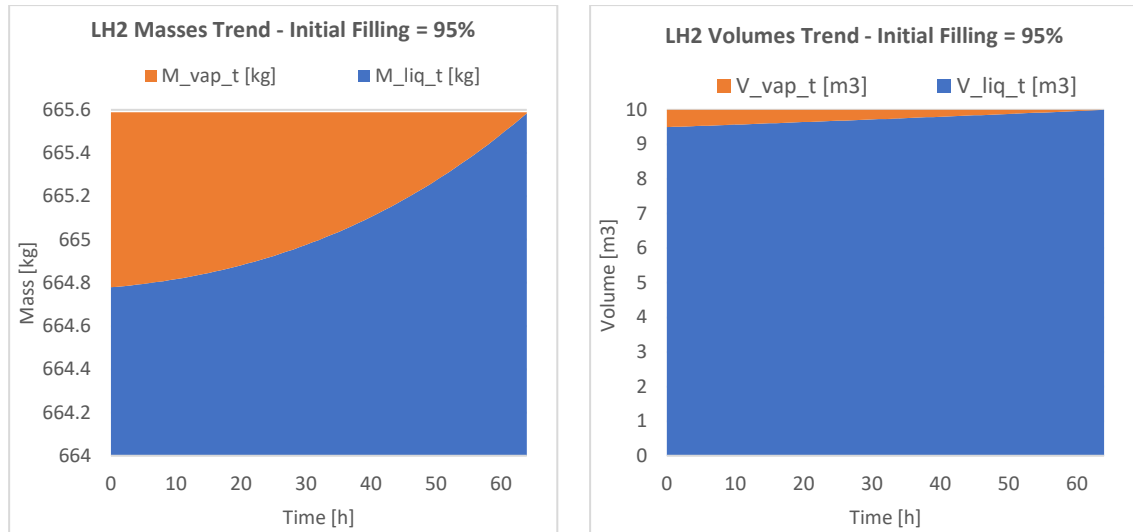


Figure 79: Progressions of liquid and vapor mass and volume throughout the simulation within the 10 m³ LH₂ plenum for initial fillings of 95%

Therefore, from the previous analysis, it is evident that a condensation boundary—defined by both saturation temperature and pressure—can be identified for different initial filling conditions. To further investigate this phenomenon, an additional analysis was conducted to determine the initial filling condition that leads to condensation once a specific temperature-pressure pair is reached. For this purpose,

Figure 80 illustrates a quadratic correlation that approximates the observed results, reported in Table 23.

Initial filling	T cond [K]	p cond [bar(a)]
5%	n.a.	n.a.
10%	n.a.	n.a.
15%	n.a.	n.a.
25%	n.a.	n.a.
35%	n.a.	n.a.
45%	32.8	12.68
50%	32.3	11.75
55%	31.6	10.52
65%	29.7	7.83
75%	27.2	5.12
85%	24.3	2.81
95%	21.0	1.26

Table 23: LH₂ Condensation temperatures and pressures for different initial fillings

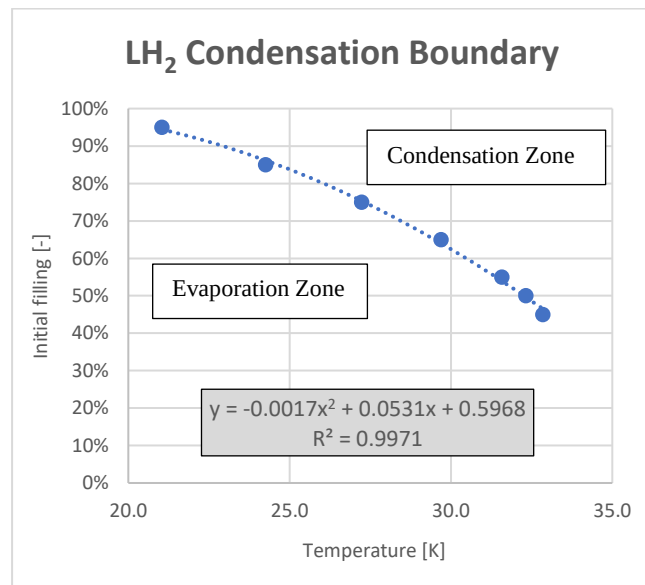


Figure 80: LH₂ Initial filling levels leading to condensation as a function of temperature

The final step of this analysis involves mapping the thermodynamic conditions over time through simulation. Accordingly, the saturation pressure and temperature are presented in [Figure 81](#) and [Figure 82](#) respectively. As can be observed, both the temperature and pressure curves exhibit interruptions due to the attainment of either unitary or zero quality.

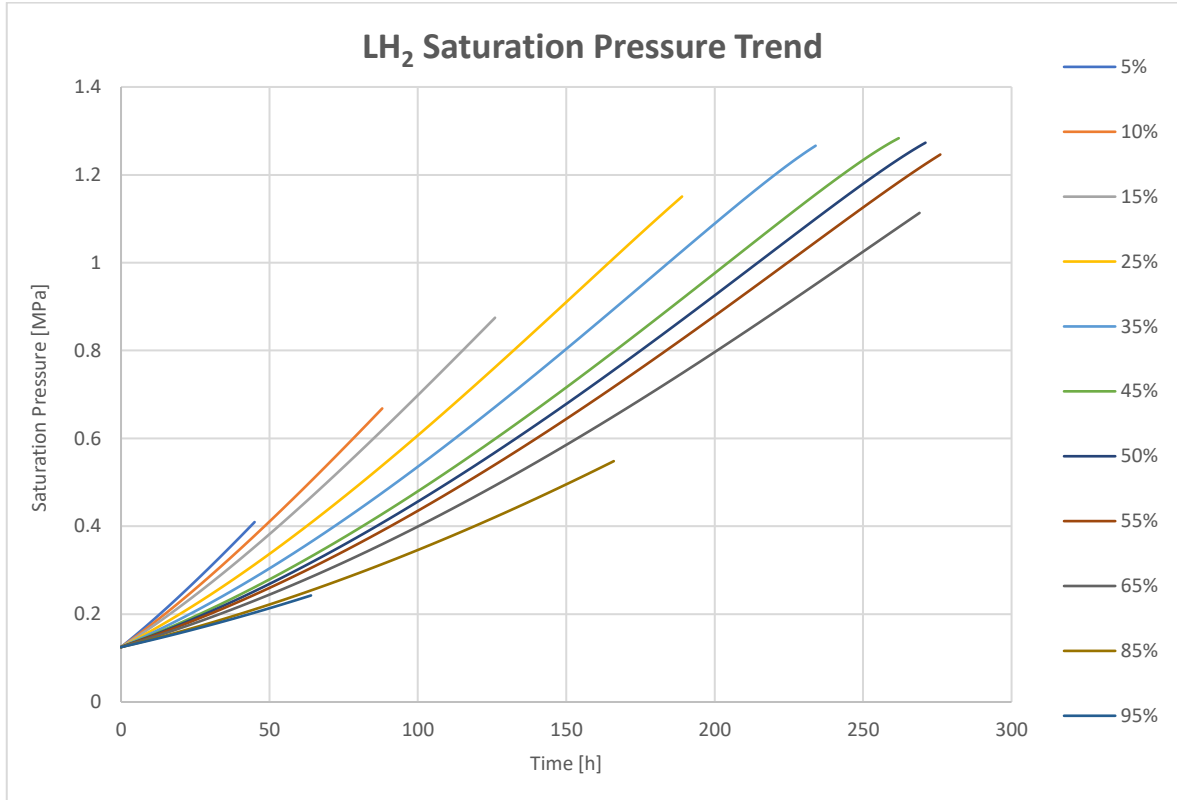


Figure 81: LH₂ saturation pressure trends for indicated initial fillings

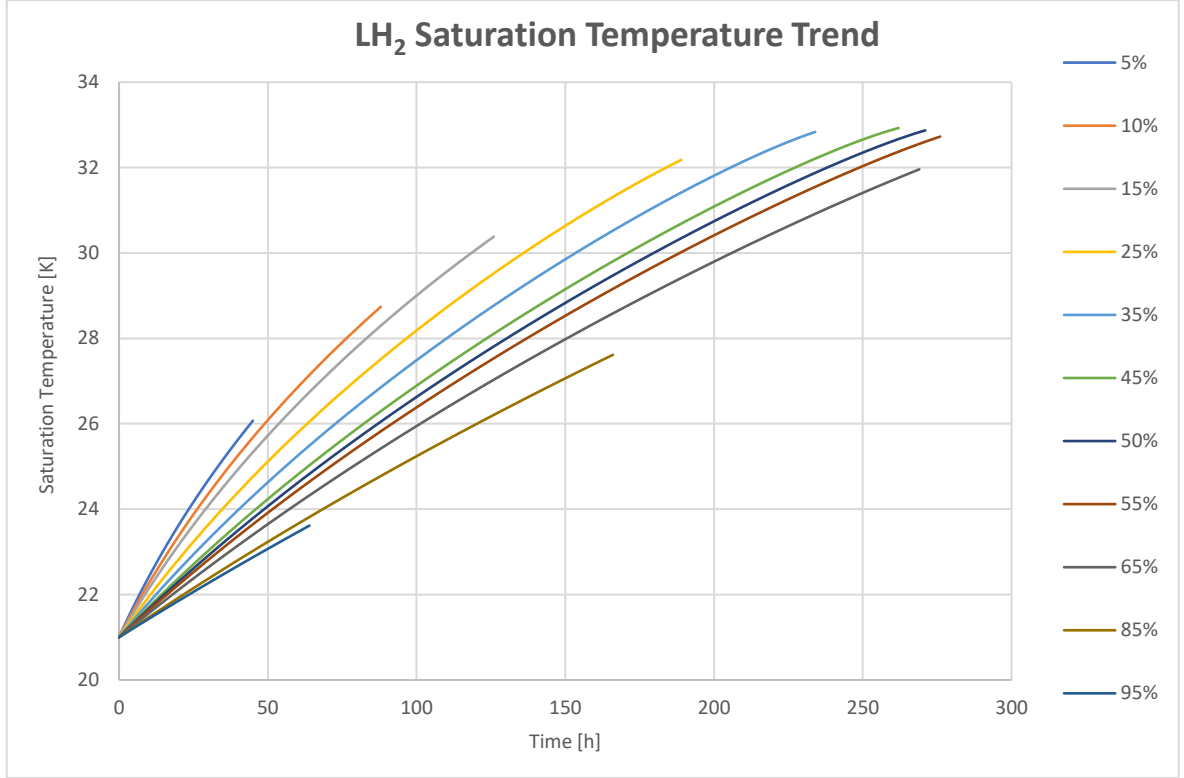


Figure 82: LH₂ saturation temperature trends for indicated initial fillings

Considering now ammonia, the same analysis conducted for hydrogen can be extended. The model has been designed to be as flexible as possible, even with regard to the type of fuel stored. By varying the type of fuel, the quality mapping for ammonia was determined for different filling levels. As shown in [Figure 83](#), the quality trends are similar; however, due to ammonia's significantly higher critical temperature (≈ 405.6 K) compared to that of hydrogen, condensation can occur at substantially higher temperatures, which are not achievable under normal operating conditions in a maritime context. [Figure 83](#) and [Figure 84](#) represents the quality and evaporated/condensed masses mapping, respectively. To obtain the presented results, the same plenum sample volume was considered, while an increased heat leak inside the tank was accounted for to accelerate the temperature rise ($V_{int} = 10m^3$ and $\dot{q} = 1,000W$). This choice was made due to the higher storage temperature of ammonia and its different chemical and physical properties.

As observed in [Figure 83](#), for low initial filling levels, the quality trends consistently increase. This happens until 35% as initial filling condition, where a sharp decrease take place close to the critical temperature. As the initial filling increases over this value, all curves exhibit a decreasing section, leading to condensation.

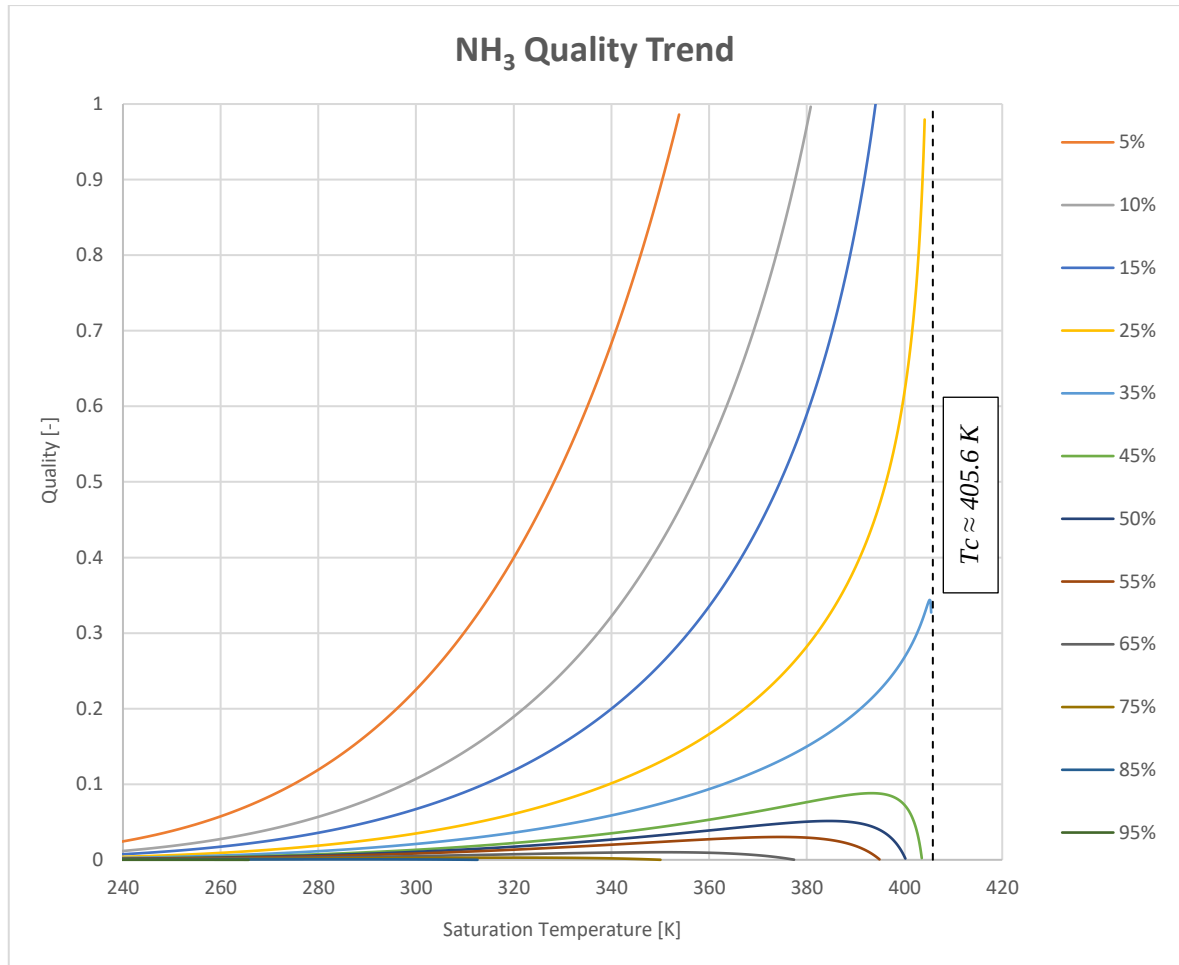


Figure 83: NH₃ quality trends for different initial fillings

Figure 84 shows that the evaporated (or condensed) mass trends are consistent with the quality mapping. In fact, all curves reach zero at their respective maximum quality points. Specifically, for a 35% filling, the rapid change in the quality trend results in a swift condensation.

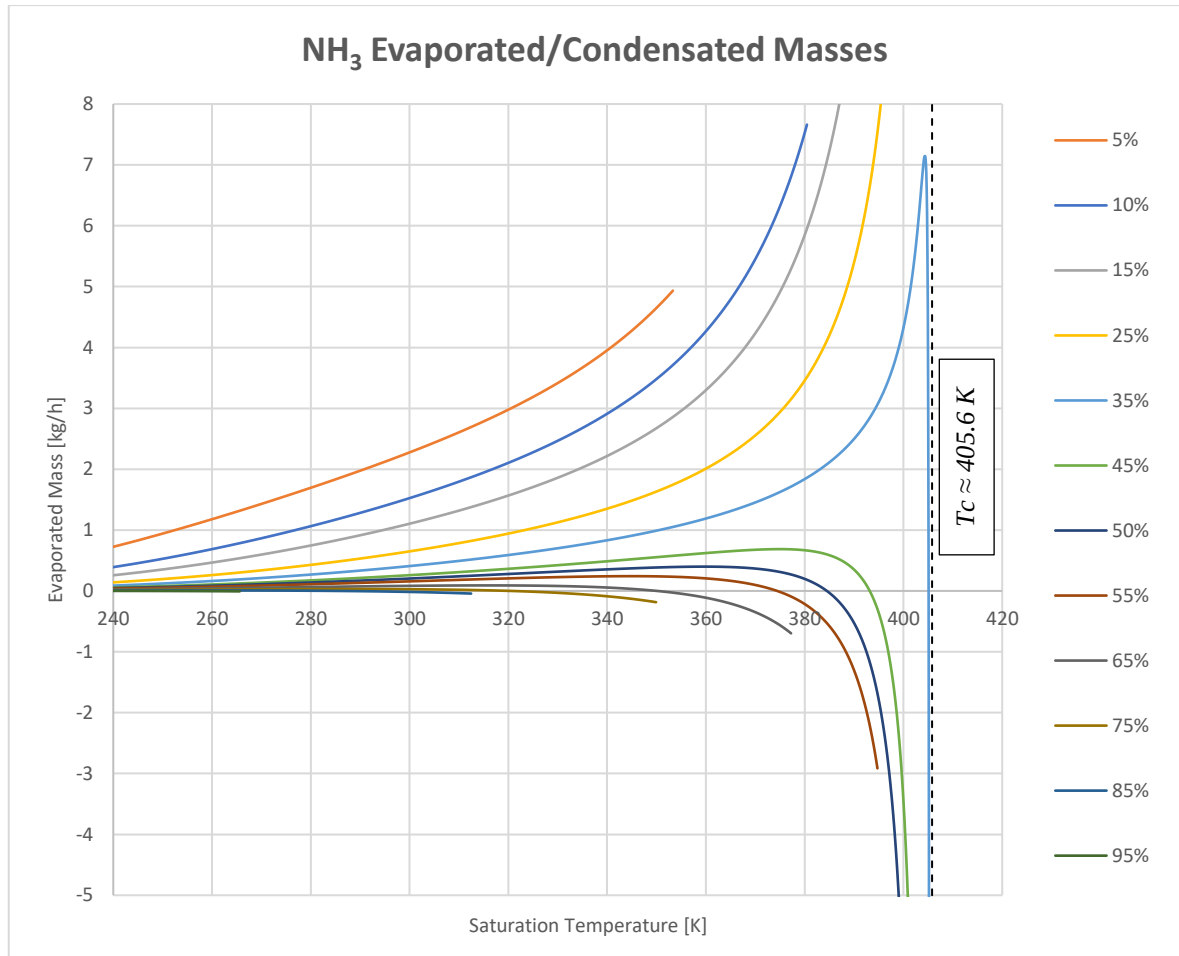


Figure 84: NH₃ evaporated/condensed masses for different initial fillings

As observed for LH₂, different behaviours of liquid and vapor masses and volumes can also be distinguished in the case of NH₃, depending on the initial conditions. To highlight these differences and enable a comparison with the previously analysed alternative fuel, the same sample values (5%, 25%, 50%, 75%, and 95%) have been considered.

Figure 85 illustrates the evolution of the liquid mass within the storage system over time. As observed for LH₂, the reduction in liquid mass due solely to evaporation, continues until complete liquid depletion. A similar decreasing trend is exhibited by the liquid volume and, consequently, by the filling level.

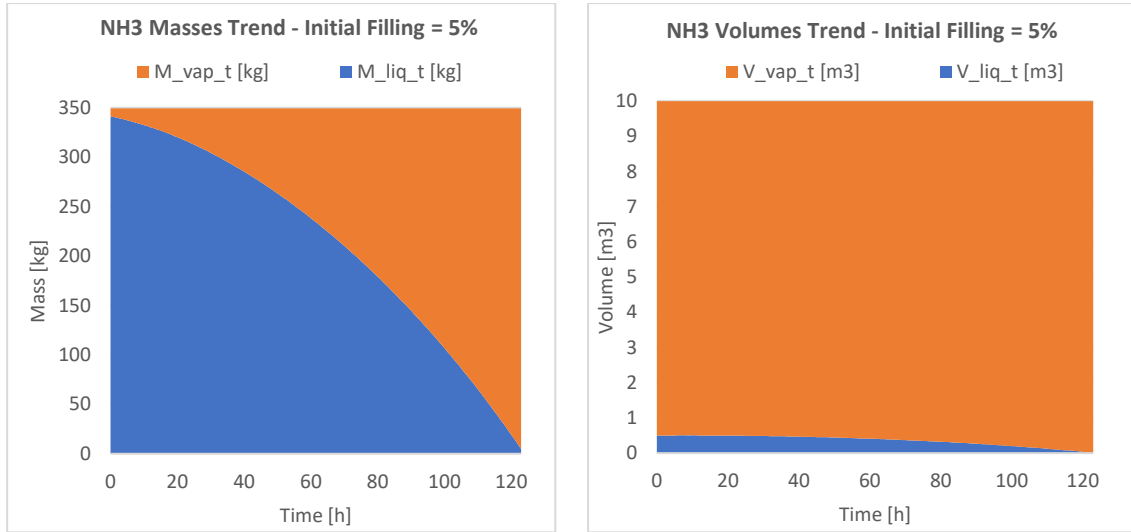


Figure 85: Progressions of liquid and vapor mass and volume throughout the simulation within the 10 m³ LH₂ plenum for initial fillings of 5%

With an initial filling level of 25% ([Figure 86](#)), the slopes of the liquid mass and liquid volume trends do not match. Unlike hydrogen, the normalized specific volume initially increases at a higher rate than the liquid mass. However, as the simulation progresses, this trend reverses, resulting in a decrease in liquid volume over approximately 300 hours. Consequently, the liquid volume—and thus the filling level—follows a non-monotonic trend over time. Nevertheless, evaporation continues throughout the simulation, ultimately leading to complete liquid depletion. This behaviour is consistent with [Figure 83](#) and [Figure 84](#).

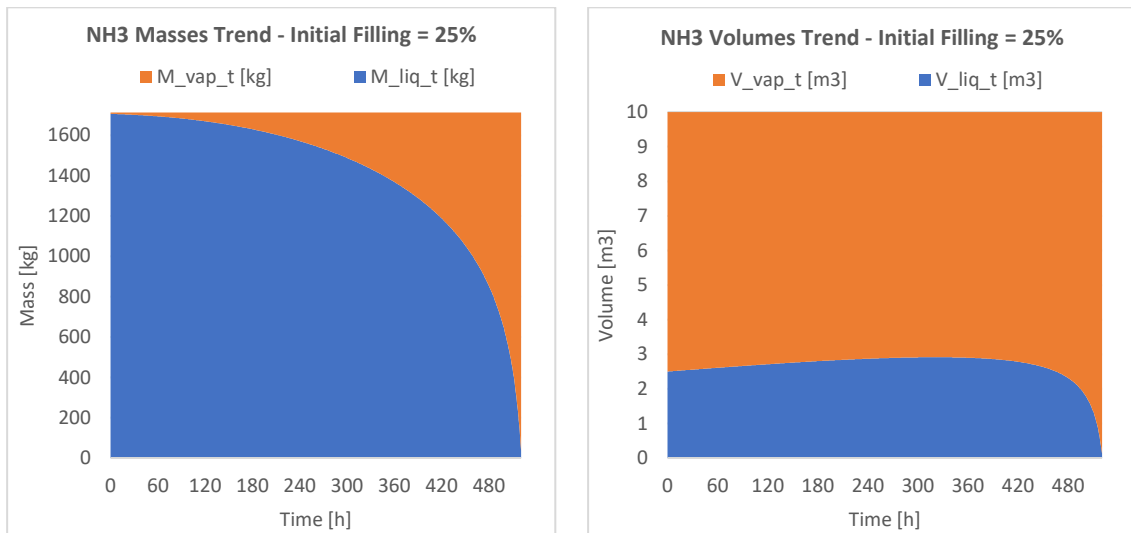
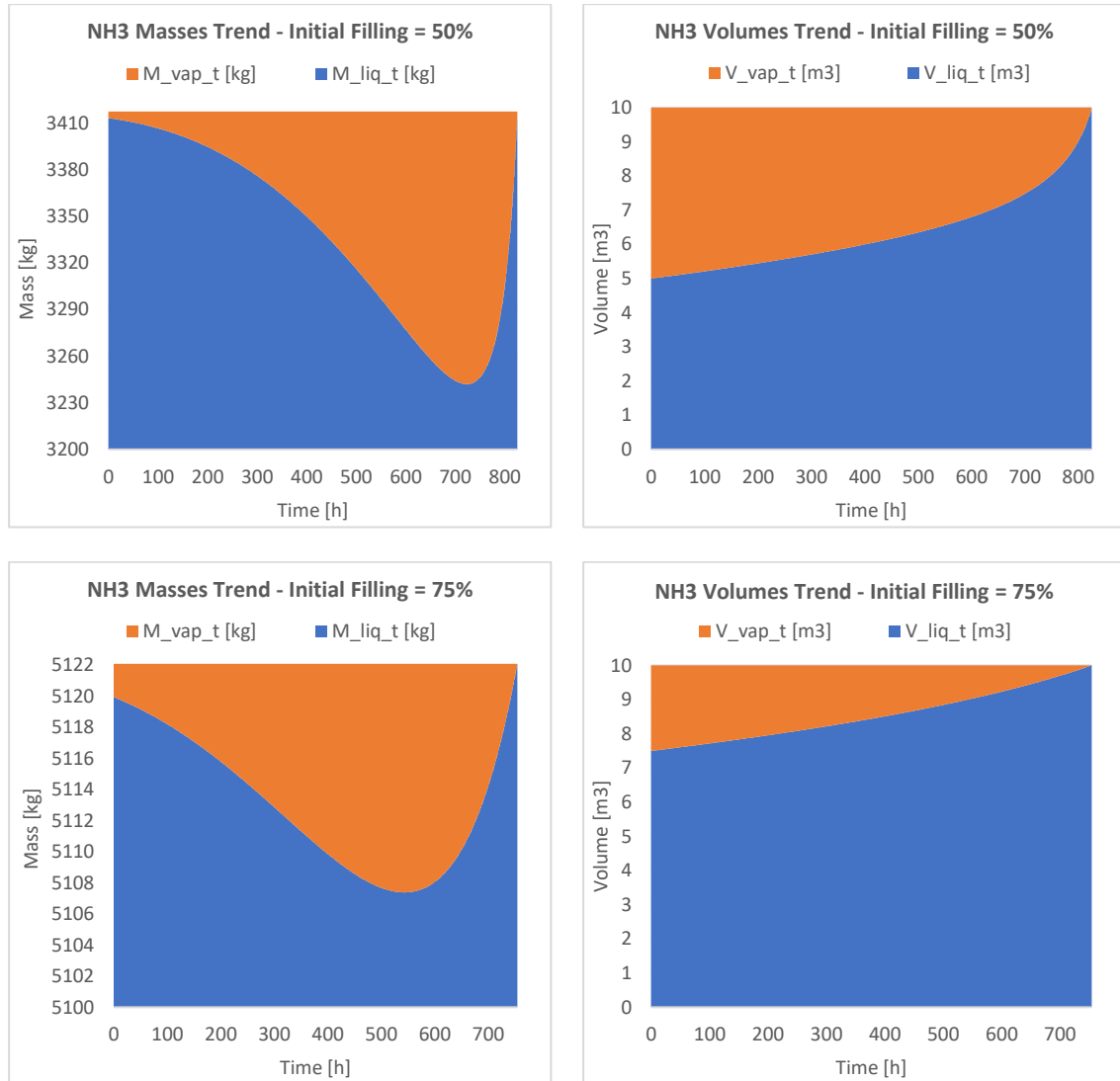


Figure 86: Progressions of liquid and vapor mass and volume throughout the simulation within the 10 m³ LH₂ plenum for initial fillings of 25%

As shown in [Figure 87](#), for initial filling levels of 50%, 75%, and 95%, the liquid mass reaches a minimum value before increasing. This indicates that condensation follows a previous evaporation phase. All these scenarios result in the complete filling of the plenum. Consistently with the behaviour observed for hydrogen at 50% and 75% initial fillings, the non-monotonic trend of liquid mass contrasts with the steady increase in liquid volume.



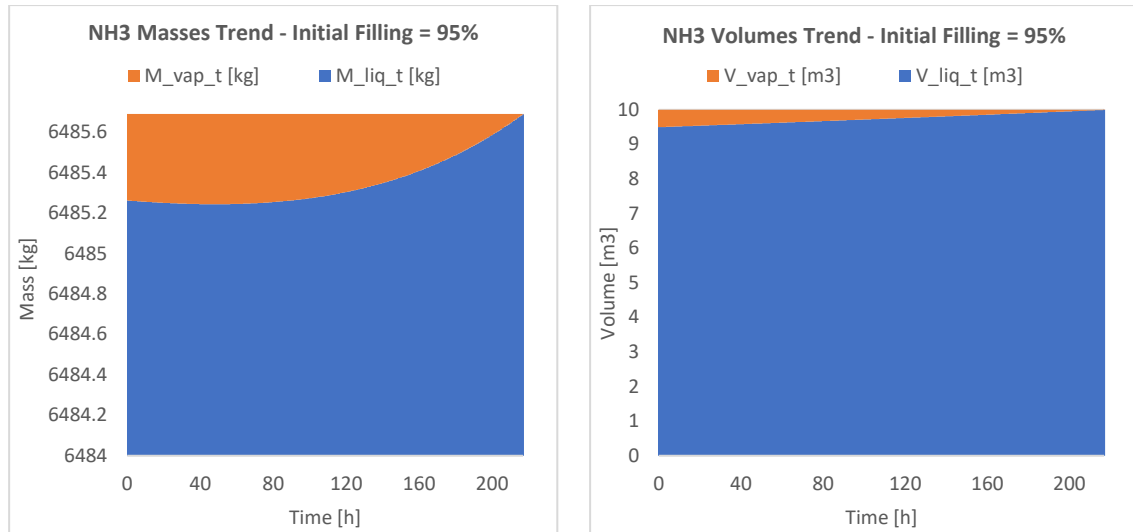


Figure 87: Progressions of liquid and vapor mass and volume throughout the simulation within the 10 m³ LH2 plenum for initial fillings of 50%, 75%, and 95%

Table 24 provides the temperature-pressure pairs at saturation conditions that, for various initial filling levels, result in condensation. As illustrated in **Figure 88**, a quadratic correlation effectively approximates the depicted function. Accordingly, considering 45°C (318.15 K) as the maximum temperature under normal operating conditions, condensation is possible only for filling levels exceeding 76.7%. It is important to note that this value holds asymptotic significance exclusively in "fully pressurized" configurations. This storage approach, feasible solely with Type-C tanks, permits design at the maximum pressure achievable under "TROPICAL" conditions (18 bar at 45°C).

Initial filling	T cond [K]	p cond [bar(a)]
5%	n.a.	n.a.
10%	n.a.	n.a.
15%	n.a.	n.a.
25%	n.a.	n.a.
35%	405.3	113.1
45%	393.5	91.6
50%	384.7	78
55%	374.6	64.4
65%	350.4	39
75%	320.8	19.1
85%	285.9	6.76
95%	245.1	1.31

Table 24: NH₃ condensation: Condensation temperatures and pressures for different initial fillings

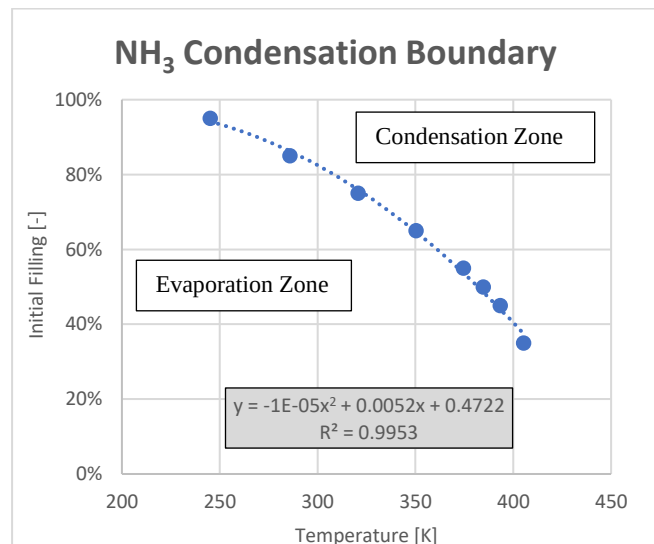


Figure 88: NH₃: Initial filling levels leading to condensation as a function of temperature

As highlighted in the LH₂ case study, [Figure 89](#) and [Figure 90](#) illustrate the trends of saturation pressure and temperature for different NH₃ initial filling levels. Similarly to the LH₂ case, the most significant pressure increase occurs at lower filling levels. However, in these cases, liquid depletion within the plenum is reached more quickly, leading to the early termination of the simulation. Consequently, the maximum pressure and temperature values remain lower than those observed for higher initial filling levels.

This trend persists up to an initial filling level of 35%. Beyond this threshold, the pressure and temperature curves exhibit a breakpoint due to the complete filling of the plenum.

From [Figure 89](#) and [Figure 90](#), when comparing this scenario with the LH₂ case study, it is evident that higher pressures are achieved in the case of ammonia. This is because both substances are brought to their respective critical points using different heat fluxes and simulation times. While LH₂ requires only a 12 K increase from the initial temperature to reach its critical point, ammonia must undergo a temperature rise of more than 166 K. This results in higher final pressure values before the simulation ends.

However, if the same heat flux were applied to both substances, a significantly longer simulation period would be required for ammonia to reach its critical conditions.

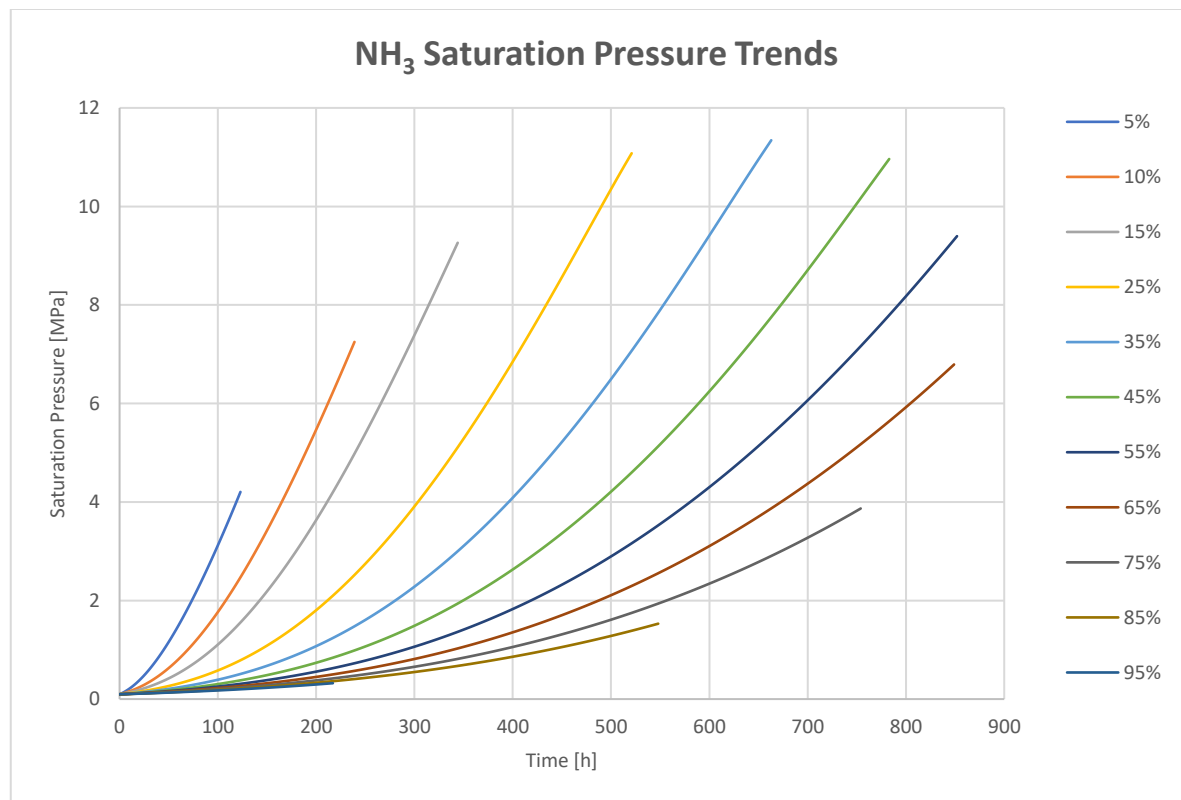


Figure 89: NH₃ saturation pressure trends for indicated initial fillings

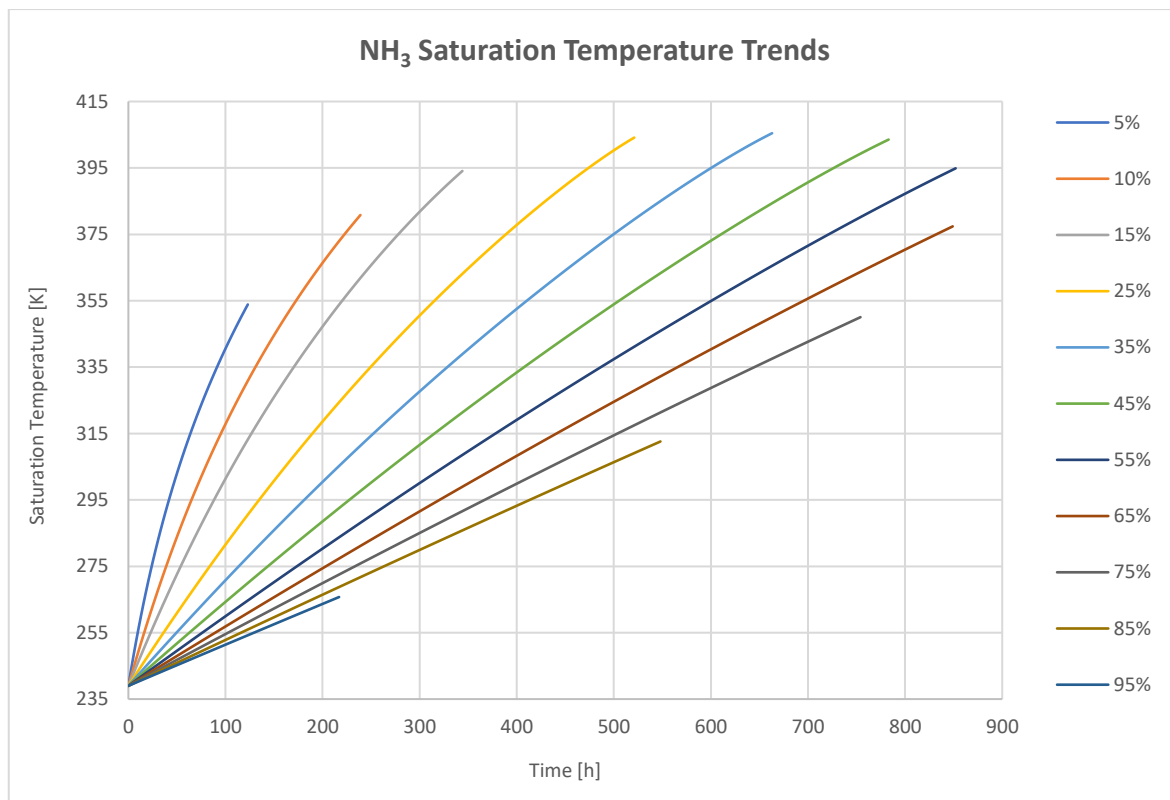


Figure 90: NH₃ saturation temperature trends for indicated initial fillings

5.3. Results and Simulations.

Once the model was used to predict the behaviour of the stored liquid over a wide temperature range—ending when the quality reaches its boundary values—two case studies were selected to extend the assessment to real-marine scenarios. The aim is to contextualize the results and introduce the modelling of additional scenarios, such as mass flow extraction or BOR treatment assessment, thereby broadening the model’s potential to gather more information about its behaviour.

5.3.1. Containership case study.

To perform simulations on the behaviour of ammonia storage as an alternative fuel for a container ship, it is essential to identify data related to a specific case study. For this purpose, a Post-Panamax container ship with a capacity of 15,000 TEU was selected as the sample vessel (*Figure 91*). This choice was driven by the availability of data on range and storage arrangements based on the fuel preparation level, as defined for the same case study in [65] e [95].



Figure 91: 15,000 TEU container vessels from Maersk as case study

Furthermore, when considering large container ships, the high propulsion power output and range requirements make alternative fuels such as ammonia or methanol particularly suitable if compared with hydrogen. Due to the significant energy to be stored onboard, hydrogen—given its low energy density—would not provide sufficient range without excessively compromising cargo capacity. Consequently, considering more relevant technical difficulties as well, this solution is deemed unsuitable for the present case study [65].

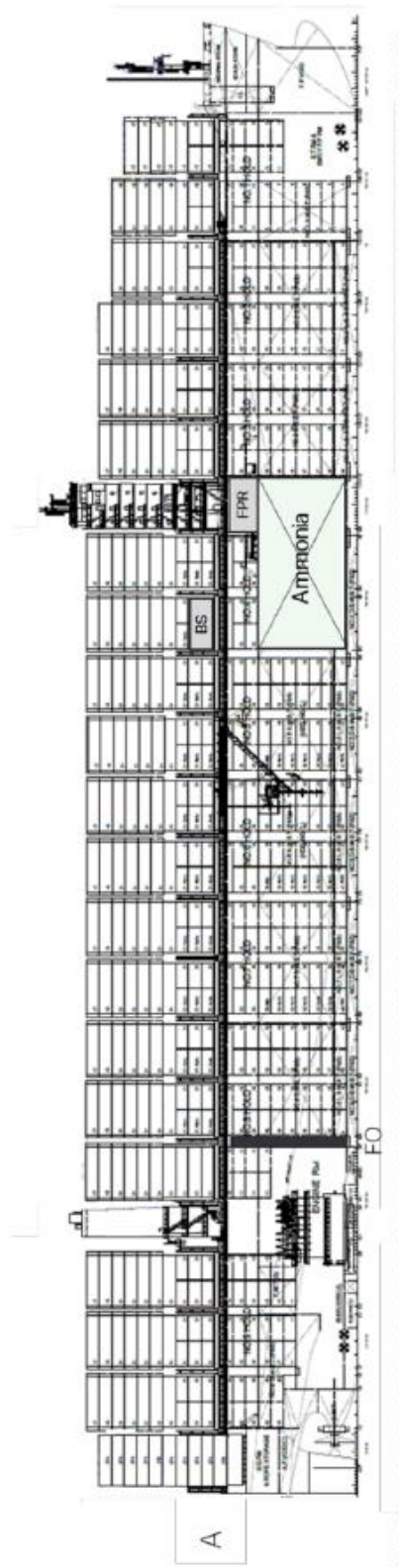


Figure 92: Ammonia storage tank arrangement for a preparation level 4 case study

For this case study, as specified in [65] a fully refrigerated Type A or B tank has been considered the best options because to the high spaces usage, due to the necessity of optimizing space saving for this kind of vessel. The original HFO fuel amount equal to $6,000 \text{ m}^3$ needs to be increase to $20,000 \text{ m}^3$ of NH_3 to maintain the same ship range. In this case a Preparation level 4 has been adopted as sample ship, since it allows to minimize the loss of cargo due to the preliminary high level space allocation. In this case, as represented in [Figure 92](#) only one ammonia Type-A, allowing to reach a maximum overpressure of 0.7 bar(g), tank was adopted.

Further specifications in terms of liquid fuel mass flow extraction for the engine feeding under different power requests are necessary to simulate the storage behaviour. This data has been extracted from [95], where a conceptual design of a same-size ammonia-fuelled container vessel has been studied. The vessel's power and propulsion concept is based on an ammonia dual-fuel two-stroke main engine with a mechanically driven shaft and propeller. The main engine considered is based on the MAN 7G90ME-C10.5 or WinGD 8X92DF-2.0 engines. Taking into account the second solution, it does not represent a commercially available technology, since this WinGD engine model is now available only LNG-fuelled, providing 42,560 kW at MCR [96]. Therefore, in order to evaluate the ammonia required amount, following assumptions have been made:

- Ammonia-MDO (as pilot) substitution ratio equal to 95% [53], as declared for commercially available ammonia-fuelled WinGD engines (X52DF-A 1.0, X62DF-A 1.0, AND X72DF-A 1.0)
- Same LNG-fuelled engine efficiency is considered for the ammonia-fuelled one.

In light to this, noted the Break Specific Energy Consumption (BSEC) [96], which need to be satisfied by the NH_3 , considering the same efficiency hypothesis, specific fuel consumption (SFC) has been calculated as in (25).

$$BSFC_{NH3} = \frac{BSEC_{tot} \cdot SR_{NH3}}{LHV_{NH3}} \quad (25)$$

Where:

- $BSFC_{NH3}$ = Ammonia Break Specific Fuel Consumption
- $BSEC_{tot}$ = Break Specific Energy Consumption required by the engine considering both alternative and pilot fuel contribution
- SR_{NH3} = Ammonia Substitution Rate
- LHV_{NH3} = Ammonia Lower Heating Value

The total NH_3 mass flow for providing 42,560 kW as maximum power (100% load) can be now evaluated by means of (26).

$$\dot{m}_{NH3} = BSFC_{NH3} \cdot P_{MCR} \quad (26)$$

Where:

- $\dot{m}_{NH3}$ = Ammonia required mass flow
- P_{MCR} = Provided power at MCR

In **Table 25** input values and obtained results are represented.

MAIN INPUTS [96]	
P_{MCR}	42,560 kW
<i>Engine N.</i>	1
$BSEC_{tot}$ (at MCR)	6,760 kW
SR_{NH3}	95%
LHV_{NH3}	18.7 MJ/kg

OBTAINED RESULTS	
$BSFC_{NH3}$	≈ 343.4 g/kWh
$\dot{m}_{NH3}$	$\approx 14,616$ kg/h

Table 25: Input values from WinGD 8X-92XDF-2.0 datasheet and obtained value in terms of ammonia required mass flow.

To carry out the simulations, two different scenario have been analysed:

- Sealed Conditions at different filling levels
- Fuel mass flow
- **Sealed Conditions at different filling levels**

For this scenario, the behaviour of ammonia stored in the tank was evaluated in terms of temperature and pressure under different filling levels. The aim of this study is to gather information about potential limitation on holding time and the resulting BOG flow rate that must be processed to prevent intolerable overpressure conditions. In this context, a 50-day simulation was conducted for multiple filling levels, highlighting scenarios where the Maximum Allowable Relief Valve Setting (MARVS) was exceeded.

To conduct this study, input data represented in **Table 26** have been considered.

MODEL INPUT – SEALED ANALYSIS		
Simulation Time	t_{end}	50 days
Timestep	Δt	1 h
Tank internal volume	V_{net}	20,000 m ³
Tank Surface	S_{tank}	$\approx 4,537.5 \text{ m}^2$
External Temperature	T_{ext}	45 °C (318.15 K)
Tank insulation Thickness	t_{ins}	0.35 m
Insulation Conductive coeff. (Perlite)	k_{ins}	$0.025 \frac{W}{mK}$
Loading Limit	LL	$\approx 96\%$
Initial Saturation Pressure	p_{in}	101,325 Pa
Initial Saturation Temperature	T_{in}	$\approx -33 \text{ °C (240.15 K)}$
Initial Filling Level	φ_0	6% to 96%
PRV set pressure	MARVS	171,325 Pa

Table 26: Input data for modelling Type-A sealed conditions for 15,000 TEU Container vessel

Based on the previous input data, in the absence of Boil-Off Gas (BOG) treatment, the maximum pressure reached inside the ammonia storage tank exceeds the MARVS only at the lowest considered filling level (6%), as shown in [Figure 93](#).

Furthermore, the same figure indicates that increasing the initial filling level from 6% to 16% allows for up to 50 days of inactivity without requiring any pressure reduction measures. Following this trend, higher initial filling levels appear to pose fewer concerns from this perspective.

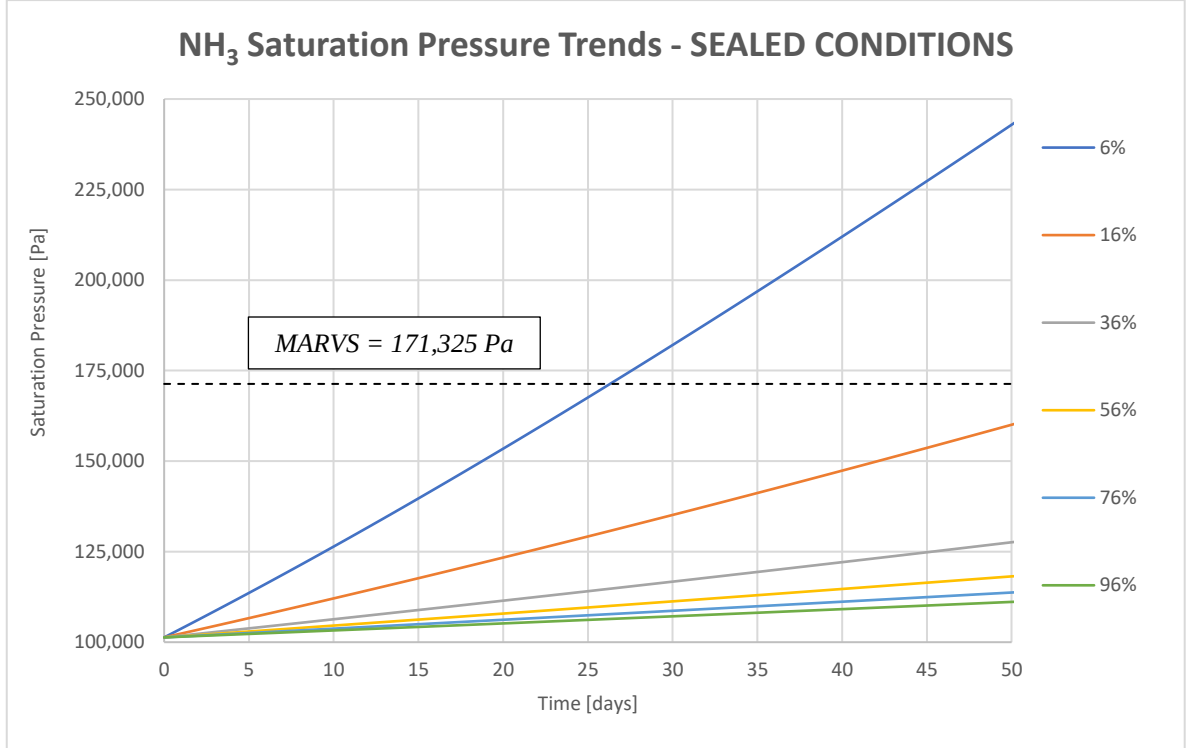


Figure 93: NH_3 saturation pressure trends during a 50-day inactivity period (sealed conditions)

The decrease in the maximum achievable pressure with increasing filling levels can be physically explained by the mass stored inside the tank. In fact, under sealed conditions ($M_{tot}(t) = \text{constant}$), when BOG extraction is omitted, the energy balance can be described as in equation (27).

$$\frac{du_{mix}(t)}{dt} = \frac{\dot{q}_{ext}(t)}{M_{tot}} \quad (27)$$

Since , the greater the mass inside the tank, the lower the increase in specific internal energy. Since the density of liquid ammonia is significantly higher than that of its gaseous phase, the filling level has a substantial impact on the total mass within the tank. Consequently, at higher filling levels, representing greater masses, the variation in internal energy decreases significantly, resulting in a reduced evaporation mass flow as well as lower saturation pressure and temperature compared to lower filling levels.

It is important to note that, since the total mass remains constant throughout the simulation, both the vapor and liquid masses evolve over time. However, this evolution does not influence the overall energy balance.

Since the model can simulate equilibrium conditions at saturation, pressure and temperature are bi-univocally defined. Accordingly, [Figure 94](#) presents the corresponding temperature trends consistent with the pressure results from the 50-day simulation.

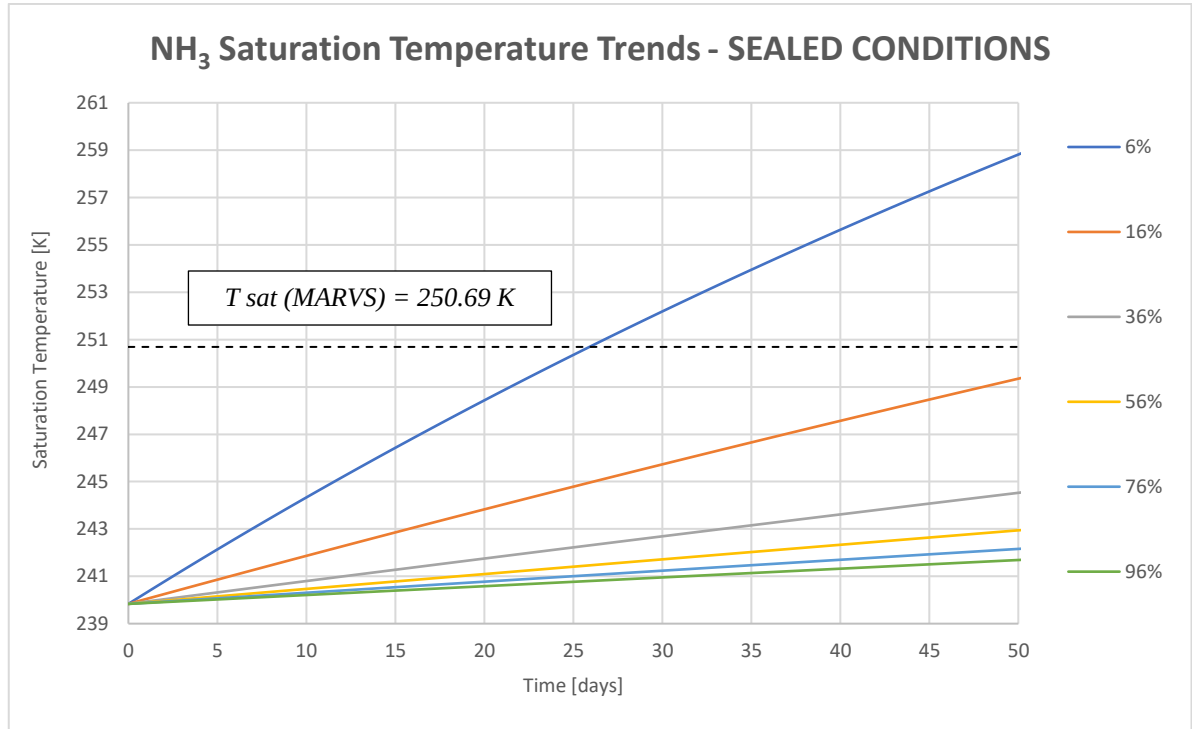


Figure 94: NH₃ saturation temperature trends during a 50-day inactivity period (sealed conditions)

[Table 27](#) reports the values obtained at the end of the described simulation, corresponding to the identified filling levels.

20,000 m ³ TANK – 50-DAYS SIMULATION FINAL RESULTS – SEALED CONDITIONS		
Initial Filling [%]	Max Pression [bar(a)]	Max Temperature [K]
6%	2.43	258.8
16%	1.60	249.3
36%	1.28	244.5
56%	1.18	242.9
76%	1.14	242.2
96%	1.11	241.7

Table 27: Final pressure and temperature after 50 days of inactivity (sealed conditions), corresponding to different initial filling levels.

Based on obtained results, it is relevant to focus on scenarios that require BOG treatment to ensure compliance with safety standards regarding overpressure.

Using the same model and setting the MARVS as the maximum allowable pressure for the selected tank type (171,325 Pa for Type-A), BOG processing will begin just before this pressure is reached, determining a mass flow rate that allows for the extraction of incoming energy.

Under sealed conditions, the total incoming energy into the system is solely due to heat transfer from the external environment. Consequently, equation (15) simplifies to (28).

$$BOR(t) = \frac{\dot{q}_{ext}(t)}{h_{vap}(t) - h_{liq}(t)} \quad (28)$$

The previous equation ensures the preservation of specific internal energy, thereby maintaining both pressure and temperature unchanged.

Following this approach, a BOR of 58.77 kg/h needs to be processed to keep the pressure below the specified threshold. For a 6% filling level, BOG management must begin after approximately 631 hours (≈ 26 days) of inactivity.

To gain a broader perspective, initial filling levels were evaluated to determine which, after 50 days of inactivity, would result in a final pressure exceeding the MARVS. This assessment was conducted to identify the range of filling levels requiring BOG treatment.

As shown in [Figure 95](#), illustrating the initial filling levels as a function of the maximum pressure reached at the end of the simulation, it is evident that BOG processing is only necessary for initial filling levels below 14% to prevent exceeding the MARVS within the 50-day simulation period. Specifically, the represented function, described by equation (29), identifies an initial filling level of approximately 13.33% as the threshold beyond which BOG treatment is not required.

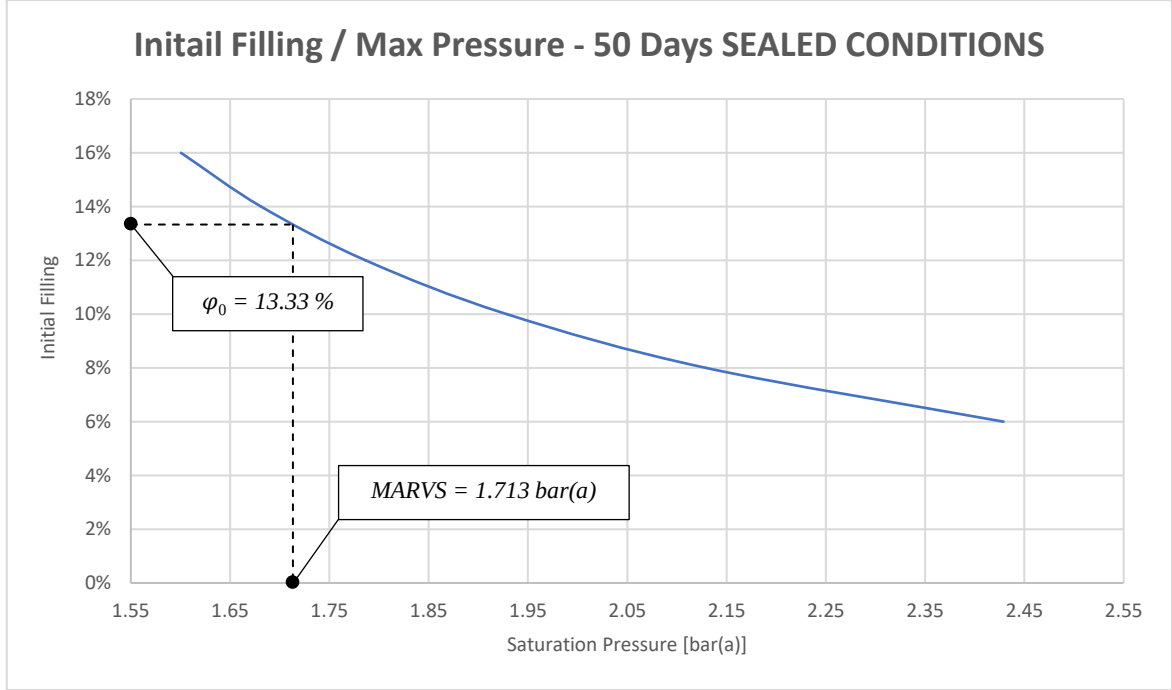


Figure 95: Correlation between the initial filling and the corresponding maximum pressure reached at the end of the 50-day sealed simulation

$$\varphi_0 = 0.16 \cdot (p_{50\text{-days}})^4 - 1.40 \cdot (p_{50\text{-days}})^3 + 4.67 \cdot (p_{50\text{-days}})^2 - 7.06 \cdot (p_{50\text{-days}}) + 4.21 \quad (29)$$

Where:

- φ_0 = Initial Filling
- $p_{50\text{-days}}$ = Final saturation presssion at the end of the 50-day inactivity simulation

It's important to note that, for each initial filling level, the amount of boil-off gas (BOR) to be processed remains the same. This is because of the pressure threshold (MARVS) at which boil-off processing has to begin. At different saturation states, this pressure corresponds to a set temperature, meaning the conditions for starting BOR processing are the same for all filling levels. What changes in the simulations is the timing of when intervention is required, as these conditions are reached at different times depending on the stored mass, which is determined by the initial filling level. As results summary, [Table 28](#) reports both the intervention time and the BOR coupled with different sample initial filling levels.

20,000 m ³ TANK - 50-DAY SIMULATION BOR RESULTS		
Initial Filling [%]	Intervention Time [days]	BOR [kg/h]
6%	≈ 26	58.77
8%	≈ 33	58.77
10%	≈ 39	58.77
12%	≈ 45	58.77
14%	> 50	0

Table 28: Time at which BOG processing system required to be activated during the 50-day sealed simulation and corresponding BOR for different initial filling levels

- **Fuel mass flow**

Following the analysis under sealed conditions, an evaluation was conducted on the controlled extraction of liquid fuel for engine supply, assuming a constant flow rate throughout the entire simulation.

The purpose of this analysis is to describe the evolution of thermodynamic conditions within the 20,000 m³ ammonia storage tank in response to potential operational requirements. Based on the mass flow assessment previously outlined, the input data for this analysis are summarized in [Table 29](#).

MODEL INPUT – LIQUID MASS FLOW ANALYSIS		
Tank internal volume	V_{net}	$20,000 \text{ m}^3$
Tank Surface	S_{tank}	$\approx 4,537.5 \text{ m}^2$
External Temperature	T_{ext}	$45 \text{ }^\circ\text{C} (318.15 \text{ K})$
Tank insulation Thickness	t_{ins}	0.35 m
Insulation Conductive coeff. (Perlite)	k_{ins}	$0.025 \frac{\text{W}}{\text{mK}}$
Loading Limit	LL	$\approx 96\%$
Initial Saturation Pressure	p_{in}	$101,325 \text{ Pa}$
Initial Saturation Temperature	T_{in}	$\approx -33 \text{ }^\circ\text{C} (240.15 \text{ K})$
Initial Filling Level	φ_0	• 6% • 96%
Liquid Fuel Mass flow	$\dot{m}_{NH_3}$	• 3,654 kg/h • 7,308 kg/h • 10,962 kg/h • 14,616 kg/h
PRV set pressure	$MARVS$	$171,325 \text{ Pa}$

Table 29: Input data for modelling Type-A tank for 15,000 TEU Container vessel under multiple mass flow rate

As indicated in the previous table, the two extreme initial filling levels (6% and 96%) are considered to represent two opposite scenarios.

Similarly, four mass flow rates—corresponding to 100%, 75%, 50%, and 25% of the maximum flow—were simulated for both initial filling levels. This approach allowed for the representation of the storage behaviour under varying engine loads.

Figure 96 illustrates the percentage variations of saturation pressure relative to the initial value and considering the lowest filling level (6%). As can be observed, the required mass flow results in rapid liquid depletion, aligning with engine demands. However, all mass flow scenarios lead to a pressure increase, albeit within a limited range.

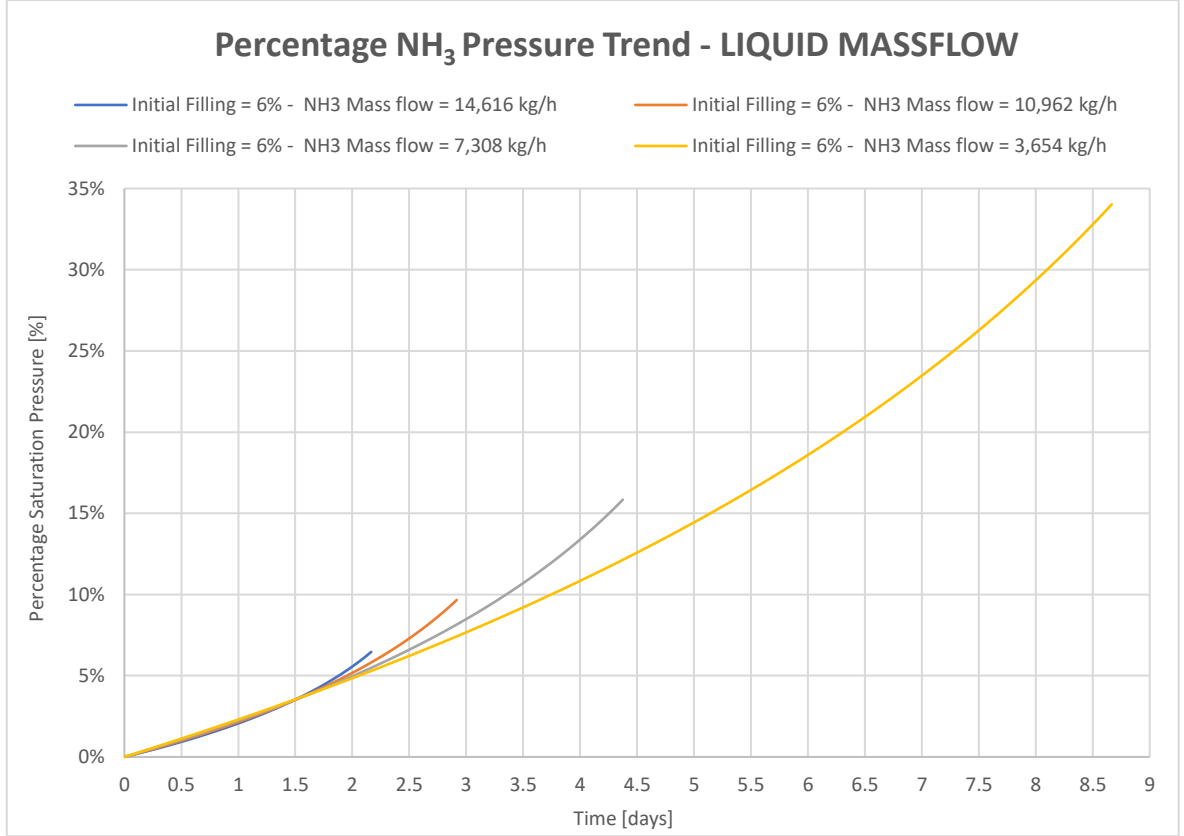


Figure 96: Percentage trends of saturation pressure for the lowest initial filling level (6%) under different sampled liquid mass flow rates.

The previous trends are influenced by both the specific internal energy and the specific volume (or density) of the mixture, as these two quantities are used to evaluate the saturation pressure and temperature.

Regarding the specific internal energy, the mass flow extraction affects it, modifying the energy balance as in (30).

$$\frac{d(u_{mix}(t) \cdot M_{tot}(t))}{dt} = \dot{q}_{ext}(t) - h_{liq}(t) \cdot \dot{m}_{engine}(t) \quad (30)$$

It is interesting to note that, for this case study, none of the considered mass flows are sufficient to reduce the specific internal energy of the mixture (u_{mix}), which exhibits an increasing trend throughout the entire simulation, as shown in [Figure 97](#).

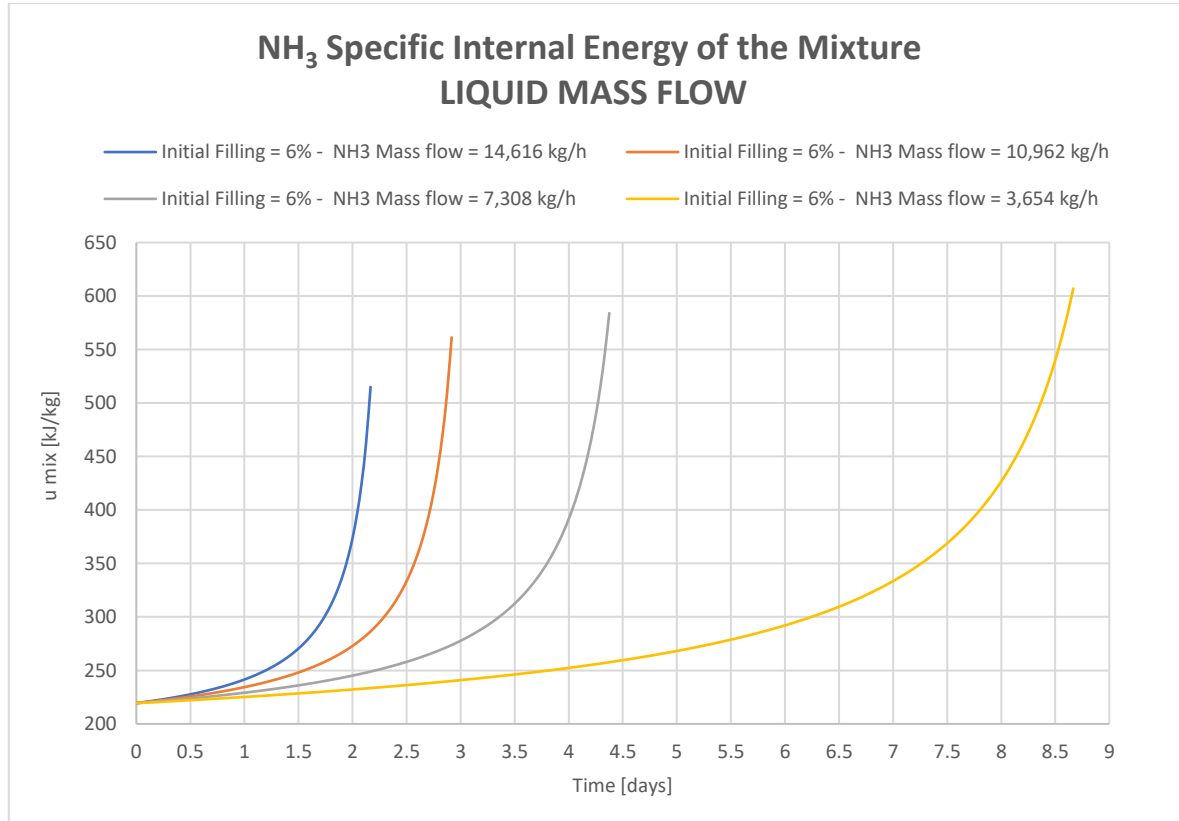


Figure 97: Specific internal energy of the mixture trends (u_{mix}) for the lowest initial filling level of 6% under different sampled liquid mass flow rates

The previous results are achieved because the extracted mass flow influences the specific internal energy from two different perspectives. The first concerns the reduction of total energy (U_{mix}) due to the energy carried away by the extracted mass flow. The second relates to the decrease in total mass that becomes significant when transitioning from a total to a specific perspective.

In light to this observation, it is important to note that, unlike specific internal energy, the total internal energy—not defined per unit mass—decreases over time as depicted in [Figure 98](#). This occurs because the energy extracted by the liquid mass flow exceeds the heat input ($h_{liq} \cdot \dot{m}_{engine} > \dot{q}_{ext}$) and it deviates from the trend of u_{mix} because U_{mix} does not account for the reduction in total mass.

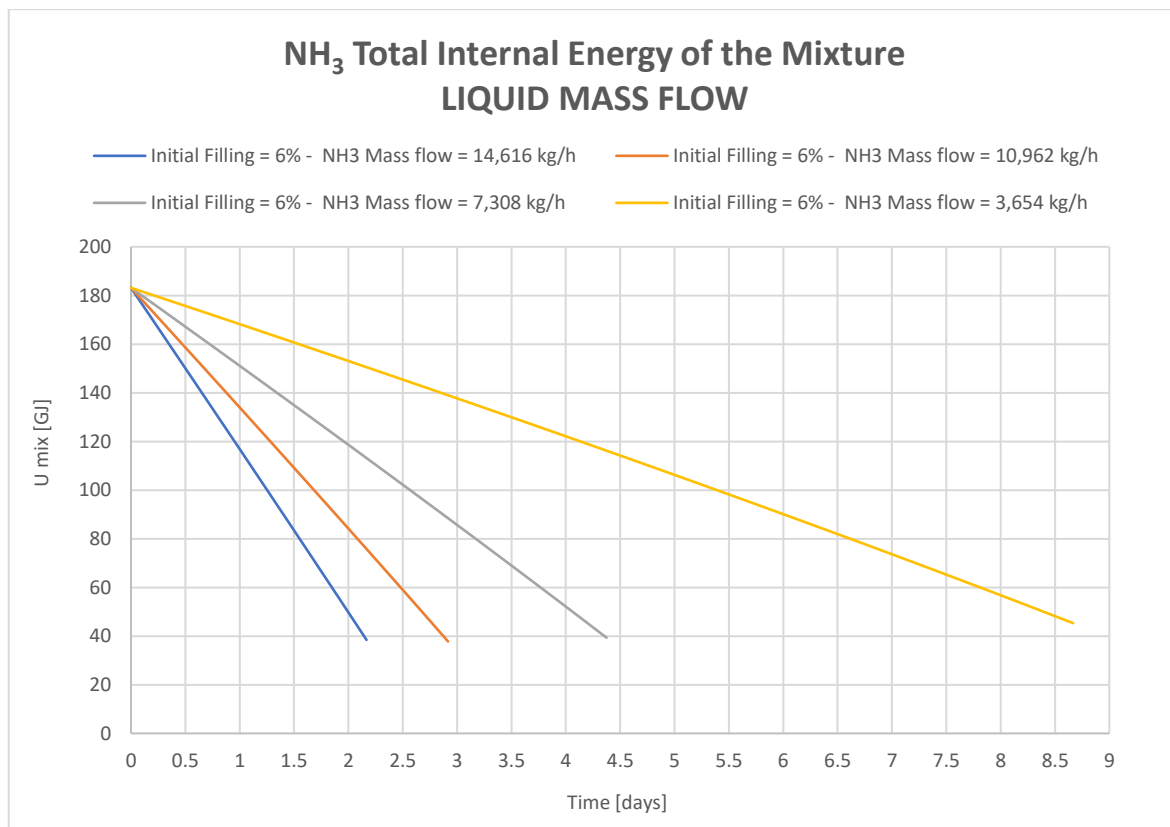


Figure 98: Total internal energy of the mixture trends (U_{mix}) for the lowest initial filling level of 6% under different sampled liquid mass flow rates

Considering now the density of the mixture as the other parameter determining the pressure, it shows a linear decrease over time, due to the significant effect of the mass flow extraction. The mixture density trends are shown in [Figure 99](#) for each sample mass flow.

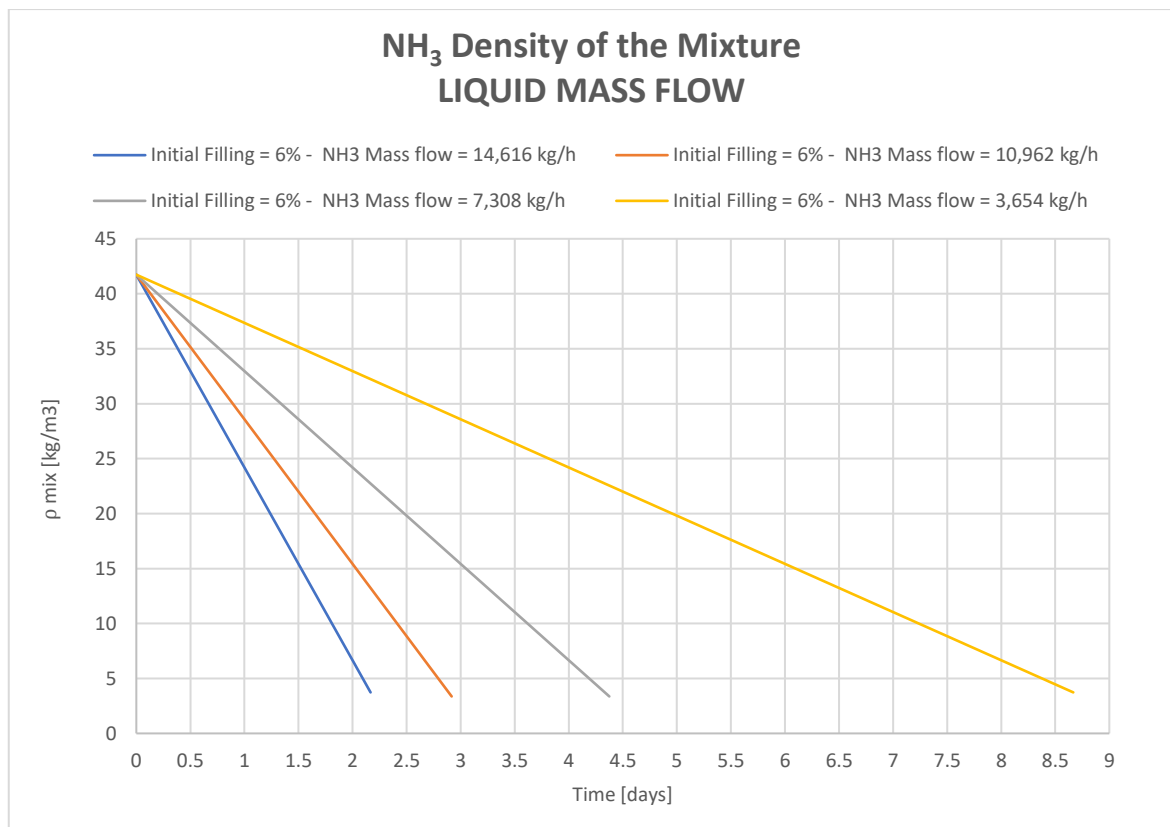


Figure 99: Density of the mixture trends (ρ_{mix}) for the lowest initial filling level of 6% under different sampled liquid mass flow rates

The different trends between the specific internal energy and the density of the mixture suggest that, depending on their relative progression throughout the simulation, pressure may either decrease or increase. This implies that an increase in specific internal energy alone is not sufficient to cause a pressure rise.

Analogously to the lowest initial filling, the same analysis was conducted for the highest filling level. The results, presented in [Figure 100](#), are consistent with the observations from the previous case. Here too, mass extraction is the primary factor driving the internal thermodynamic conditions. In general, similar pressure increasing trends were observed with an initial filling level of 96%. In this case, higher final values were reached due to the longer simulation time, as it takes more time to fully deplete the liquid within the tank. Specifically, for the lowest mass flow rate (3.654 kg/h), the saturation pressure exceeds the MARVS, requiring the activation of the BOG management system, which needs to process of about 50.8 kg/h.

However, it is important to note that the simulation was extended until complete liquid depletion, deviating from realistic navigation conditions, where continuous navigation periods are typically much shorter than 150 days.

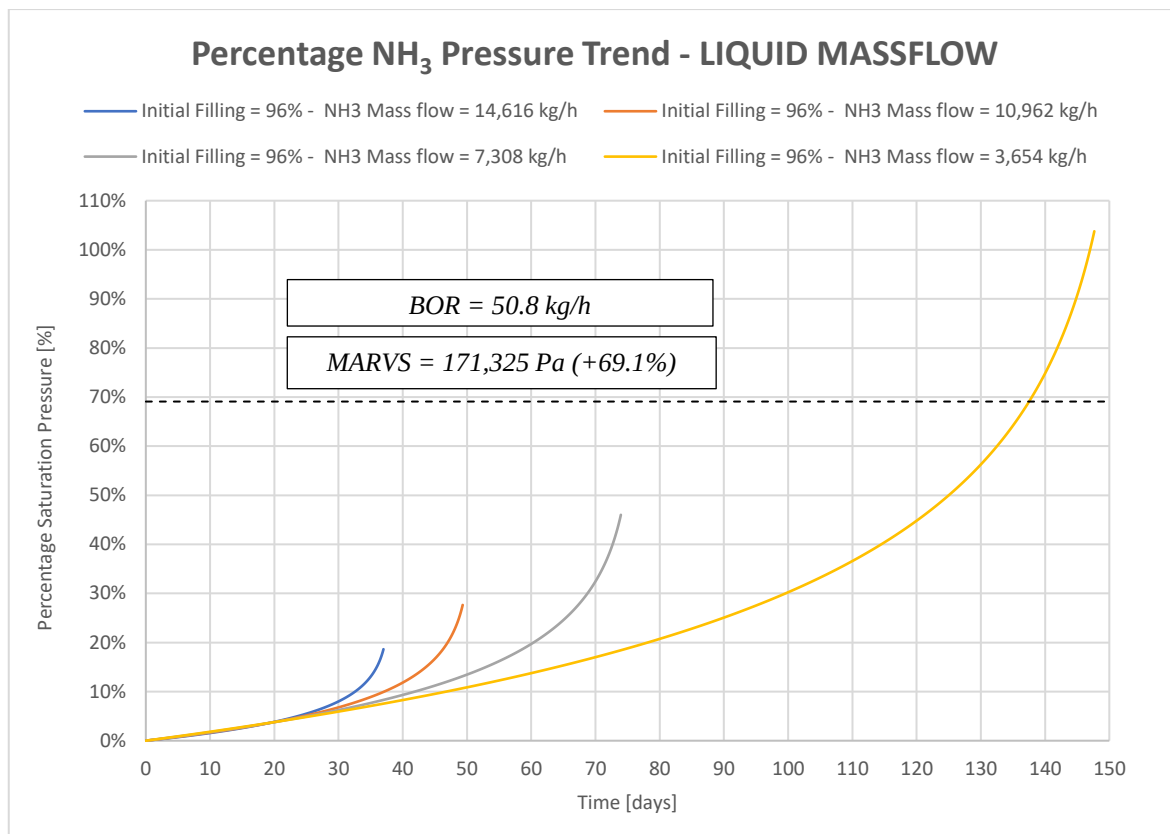


Figure 100: Saturation pressure trends for the lowest initial filling level of 96% under different sampled liquid mass flow rates

This analysis highlights that, due to the extremely large amount of fuel contained within a 20,000 m³ Type-A tank—required to achieve the same range as a 6,000 m³ of MDO for a 15,000 TEU containership—its impact on pressure build-up in the sealed analysis is not significant. Similarly, because of the high ammonia volume, the required mass flow does not pose a risk of potential under-pressurization of the tank.

Since these phenomena are closely related to stored total mass, it becomes important to understand how storage behaviour changes with different tank sizes. To investigate this, a significantly smaller Type-C tank, used for cruise ship storage, has been analysed, starting from an LNG-fuelled vessel as baseline.

5.3.2. Cruise ship case study

Ship type	Size category	Unit	Number of vessels				Avg. main engine power (kW)	Avg. design speed (kn)	Avg. days at sea	Avg. days international	Avg. days in SECA	Avg. SOG at sea (kn)	Avg. Distance sailed (nm)	Median AER	Avg. consumption (kt)			Total GHG emissions (in million tonnes CO ₂ e)	Total CO ₂ emissions (in million tonnes)
			Type 1 and 2	Type 3	Type 4	Type 4									Main	Aux.	Boiler		
Cruise	0-1999	gt	126	641	45	0	3,115	12.7	93	17	74	8.1	18,975	3,770.5	0.1	0.4	2.2	1.7	1.7
	2000-9999	gt	110	0	0	0	867	13.8	148	109	63	9.2	33,335	513.4	0.5	0.8	1.8	1.1	1.1
	10000-59999	gt	105	0	0	0	4,018	19,378	206	232	63	13.4	66,624	147.3	5.0	6.4	1.4	4.3	4.2
	60000-99999	gt	98	0	0	0	8,249	21.8	256	272	94	15.3	94,193	155.2	16.1	20.3	1.0	11.6	11.4
	100000-149999	gt	61	0	0	0	10,935	21.3	250	295	96	16.0	96,582	140.5	24.4	20.0	1.0	8.8	8.6
	150000+	gt	21	0	0	0	13,499	22.0	236	301	58	16.4	92,891	109.6	23.2	19.8	1.2	2.9	2.9

Figure 101: Cruise ship global fleet average features, defined by IMO 4th GHG study

In order to identify useful data for running the simulations, and in the absence of a reference case study, average installed power values on board were used, as shown in [Figure 101](#) [54]. Specifically, the size bin of 60,000 – 99,999 GT was considered as indicative, as this category corresponds to the highest total GHG emissions, as reported in the same [Figure 101](#). Based on this assumption, an average installed power of 51,518 kW is indicated.

In general, modern cruise ships have higher installed power than what is required to meet maximum propulsion and hotel load demands. Additionally, this power is typically distributed across multiple diesel generator sets (D/G) to ensure a high level of redundancy. Unlike the previous case study, which featured a single large 2-stroke engine directly coupled to the propeller shaft, in this case, the D/G units couple medium-speed 4-stroke engines with alternators to generate electrical power, which is then redistributed to the ship's systems. In this scenario, propulsion is provided by electric motors coupled to the propellers via a shaft line or “azipod” technology, achieving full electrification of the propulsion loads. The choice of 4-stroke main engines on these ships is mainly driven by the smaller height and better matching of engine speed with the alternators.

Based on these initial considerations, four LNG DF-ICE Wartsila 9L46TSDF [97] —each providing 11,700 kW and collectively achieving 46,800 kW—were chosen as case study for the simulation.

Regarding the storage system, since an LNG case study is considered as the baseline, two bilobed storage tanks have been selected while keeping the stored volume unchanged, as represented in *Figure 102* [98].

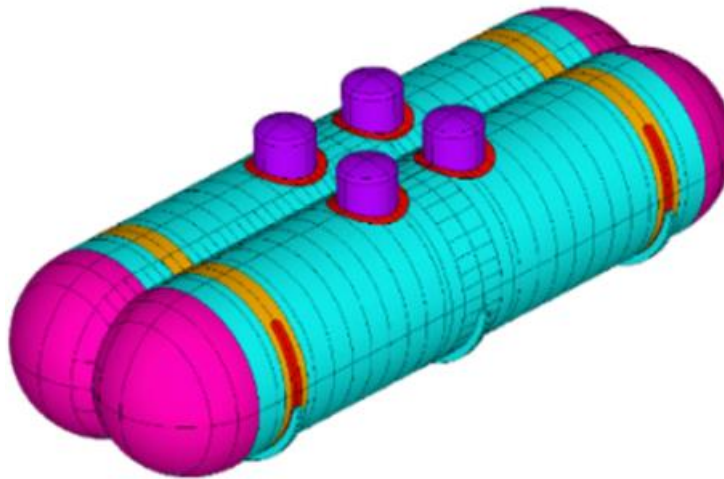


Figure 102: Sample of bi-lobed type-C tanks.

This choice was made primarily for two reasons:

1. A retrofitting scenario was simulated, where the allocation of spaces dedicated to storage tanks cannot be modified.
2. Cruise ships make port calls much more frequently than large container vessels. Therefore, the reduction in ship range was considered less impactful on operational feasibility, as it is assumed that the vessel can refuel more frequently in port. However, this assumption does not account for the actual availability of bunkering infrastructure when ammonia is used.

It is important to note that this analysis, which takes LNG as a baseline, does not consider the compatibility of tank materials with ammonia. In a retrofitting scenario, where the same LNG storage systems are to be used, conducting a thorough material compatibility assessment is crucial.

In light to previous assumptions a total storage volume of 2,500 m³ of LNG, distributed between two Type-C tanks, has been maintained when switching to ammonia.

For evaluating the maximum required mass flow from the engines, 85% has been considered as load for reaching the highest speed, characterizing the highest energy request for this simulation. All for

D/G are considered working at previous condition. In this scenario 39,780 kW has been identified as required power.

Considering the possibility to retrofit the LNG DF-ICE to run with ammonia engine retrofitting, same considerations carried out for containerhips were adopted, and reported below:

- Ammonia-MDO (as pilot) substitution ratio equal to 95% [53], as declared for commercially available ammonia-fuelled WinGD engines (X52DF-A 1.0, X62DF-A 1.0, AND X72DF-A 1.0). The same value was assumed for this application.
- Same LNG-fuelled engine efficiency is considered for the ammonia-fuelled one.

Therefore, by applying the same approach used to identify the NH₃ BSFC in the case of the containership—described by (25) and (26)—a total mass flow of approximately 14,490 kg/h has been determined to meet the previously specified power requirements.

Main initial engine data and obtained results are resumed in [Table 30](#).

MAIN INPUTS [97]	
P_{MCR}	11,700 kW
<i>Engine N.</i>	4
P_{TOT}	46,800 kW
P_{TOT} (at 85% MCR)	39,780 kW
$BSEC_{tot}$ (at 85% MCR)	7,170 kJ/kWh
SR_{NH_3}	95%
LHV_{NH_3}	18.7 MJ/kg

OBTAINED RESULTS	
$BSFC_{NH_3}$ (at 85% MCR)	≈ 364.2 g/kWh
$\dot{m}_{NH_3}$	≈ 14,490 kg/h

Table 30: Input from Wartsila 9L46TSDF datasheet and obtained value in terms of ammonia required mass flow.

Also in this case following scenarios were considered for conducting simulations:

- Sealed Conditions at different filling levels
- Fuel mass flow

- **Sealed Conditions at different filling levels**

Starting from the sealed conditions in this case, the assumption of using a Type-C tank allows for a broader range of achievable maximum pressures. For this application, a MARVS of 4 bar(a) has been considered. However, fully pressurized Type-C tanks specifically designed for onboard ammonia storage are commercially available [99]. To achieve fully pressurized conditions, a pressure of 18 bar(a) must be considered, as this corresponds to the saturation pressure at 45°C. If this condition is assumed, no limitations on holding time occur.

To enable a more direct comparison in this case study, the MARVS of the Type-C tank has been compared with that of the previous Type-A tank, emphasizing the reduction in holding time.

The values assumed as simulation inputs are summarized in [Table 31](#).

MODEL INPUT – SEALED ANALYSIS		
Simulation Time	t_{end}	50 days
Timestep	Δt	1 h
Single tank internal volume	V_{net}	1,250 m ³
Tank Surface	S_{tank}	≈ 785 m ²
External Temperature	T_{ext}	45 °C (318.15 K)
Tank insulation Thickness	t_{ins}	0.35 m
Insulation Conductive coeff. (Perlite)	k_{ins}	0.025 $\frac{W}{mK}$
Loading Limit	LL	≈ 92 %
Initial Saturation Pressure	p_{in}	101,325 Pa
Initial Saturation Temperature	T_{in}	≈ −33 °C (240.15 K)
Initial Filling Level	φ_0	5% to 92%
PRV set pressure	MARVS (Type – C)	401,325 Pa
	MARVS (Type – A)	171,325 Pa

Table 31: Input data for modelling Type-C tank for Cruise vessel in sealed conditions

As shown in [Figure 103](#), which represents a 50-day simulation under sealed conditions, smaller tanks exhibit worse performance in terms of pressure and temperature rise when subjected to the same external conditions and insulation characteristics. This is primarily due to the lower ammonia mass within the tank, which drives the process.

However, when compared to the Type-A tank installed on the 15,000 TEU containership, the heat transfer surface area is significantly smaller. Nonetheless, as indicated in [Table 32](#), the ratio between the tank's boundary surface and its available volume—directly related to the stored mass—is higher for the parallelepiped-shaped Type-A tank. This implies that, per unit of volume, the Type-C tank has a larger lateral surface area due to both its different size and shape.

Under identical external and internal conditions, as well as insulation properties, this results in a higher heat flux per unit volume (or mass) for the Type-C tank.

	15,000 TEU Containership Type-A	Cruise Type-C
Volume	20,000 m^3	1,250 m^3
Lateral Surface	4,537.5 m^2	785 m^2
Surface Coff. per unit volume	0.227 m^{-1}	0.628 m^{-1}

Table 32: Geometrical features comparison between 20,000 m^3 Type-A and 1,250 m^3 Type-C tank

[Figure 103](#) illustrates that, for the small Type-C tank, an initial filling level of 5% is the most critical condition, reaching the MARVS of 401,325 Pa in approximately 32 days, while higher initial fillings do not present any issues.

For comparison, the MARVS of the Type-A tank, set at 171,325 Pa, is also shown on the same graph. In this case, initial filling levels of 5%, 15%, and 35% result in critical conditions, requiring the activation of the BOG management system to reduce pressure. Specifically, a BOR of 10.2 kg/h and 7.4 kg/h needs to be processed for a MARVS of 171,325 Pa and 401,325 Pa, respectively.

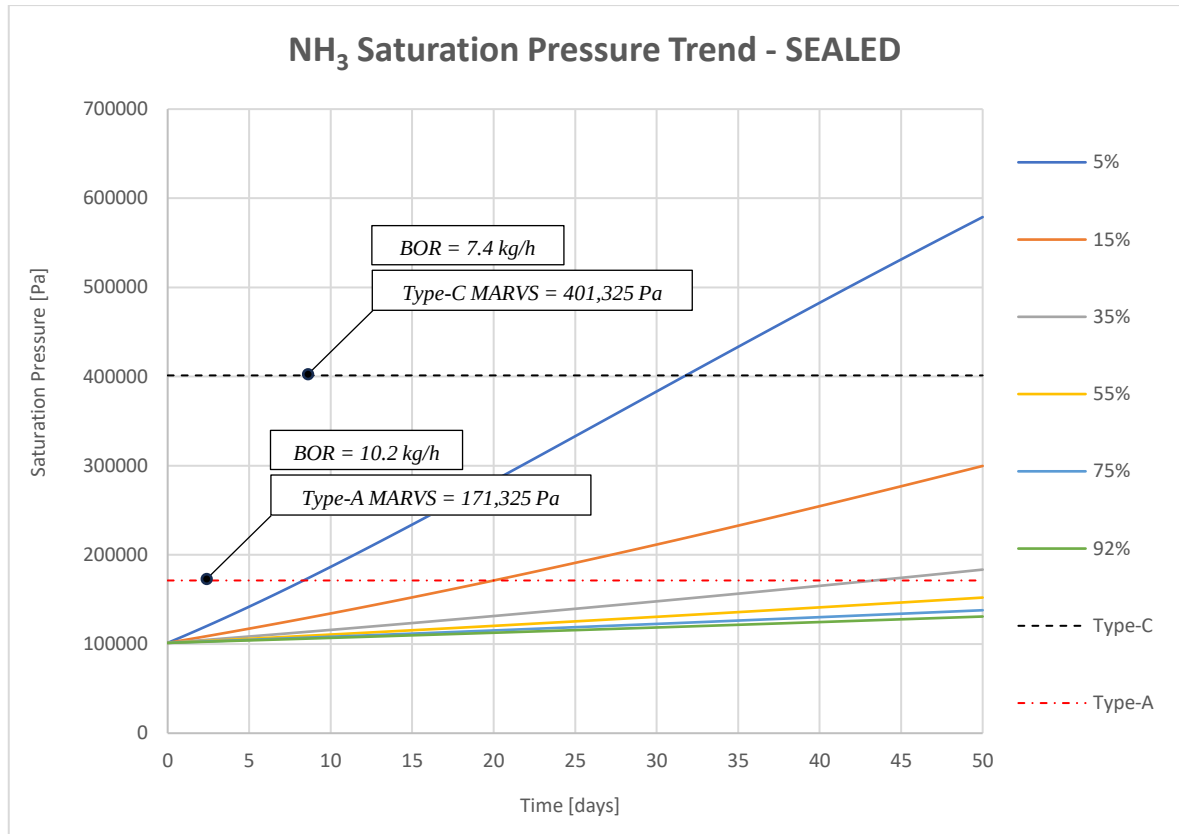


Figure 103: NH₃ saturation pressure trends during a 50-day inactivity period (sealed conditions)

As done in the previous case study, the corresponding saturation temperature trends are presented in [Figure 104](#). The MARVS limitations have been expressed in terms of the corresponding saturation temperature.

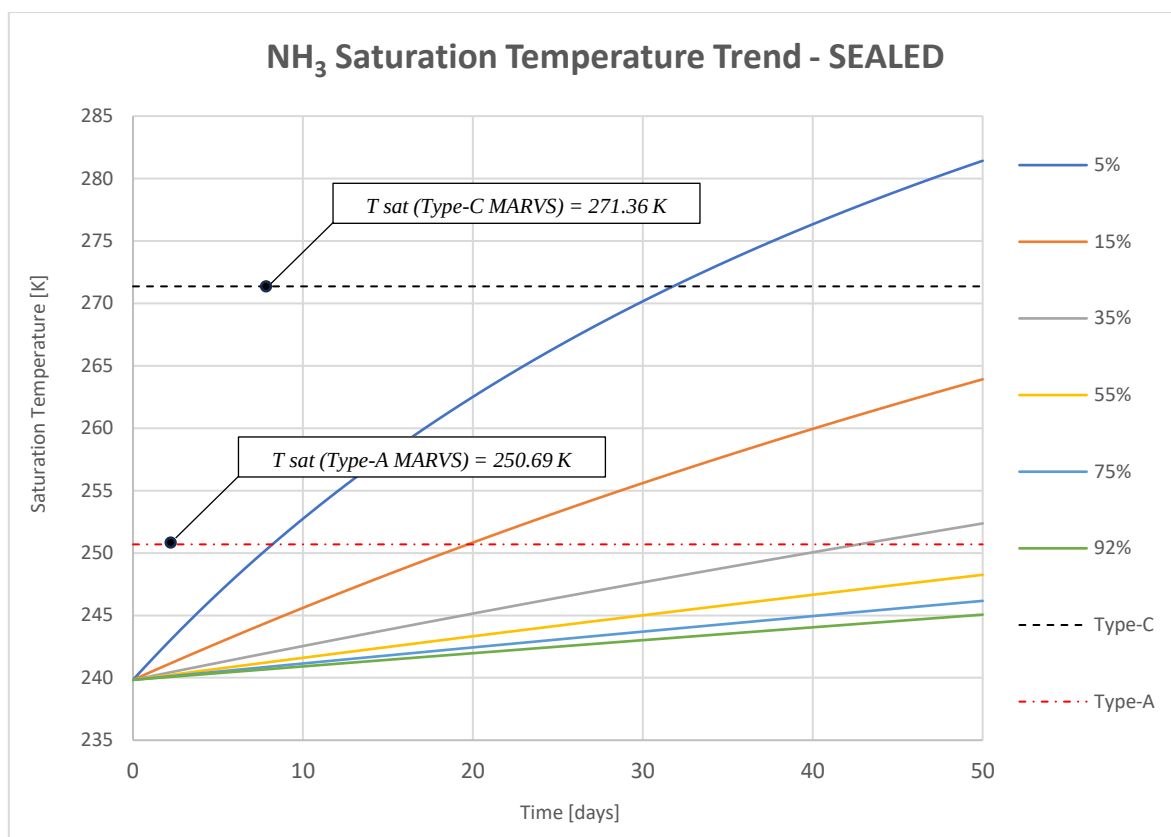


Figure 104: NH₃ saturation temperature trends during a 50-day inactivity period (sealed conditions)

Table 33 summarizes the results obtained from the 50-day sealed simulation for the 1,250 m³ Type-C tank.

1,250 m ³ TANK - 50-DAYS SIMULATION FINAL RESULTS SEALED CONDITIONS		
Initial Filling [%]	Max Pression [bar(a)]	Max Temperature [K]
5%	5.79	281.4
15%	3.00	263.9
35%	1.84	252.4
55%	1.52	248.3
75%	1.38	246.2
92%	1.31	245.1

Table 33: Final pressure and temperature after 50 days of inactivity (sealed conditions), corresponding to different initial filling levels.

- **Fuel Mass flow**

The primary focus of the reduced-size Type-C tank simulation is to analyse its behaviour under significant mass extraction. Therefore, as in the previous case, a constant fuel extraction rate, based on potential engine demands, was simulated throughout the entire duration. The initial data are summarized in [Table 34](#).

MODEL INPUT – LIQUID MASS FLOW ANALYSIS		
Tank internal volume	V_{net}	1,250 m ³
Tank Surface	S_{tank}	≈ 785 m ²
External Temperature	T_{ext}	45 °C (318.15 K)
Tank insulation Thickness	t_{ins}	0.35 m
Insulation Conductive coeff. (Perlite)	k_{ins}	0.025 $\frac{W}{mK}$
Loading Limit	LL	≈ 92%
Initial Saturation Pressure	p_{in}	101,325 Pa
Initial Saturation Temperature	T_{in}	≈ −33 °C (240.15 K)
Initial Filling Level	φ_0	92%
Liquid Fuel Mass flow	$\dot{m}_{NH_3}$	• 3,623 kg/h • 7,245 kg/h • 10,686 kg/h • 14,490 kg/h
PRV set pressure	$MAWP$	401,325 Pa

Table 34: Input data for modelling Type-C tank for a cruise vessel under multiple mass flow rate

In this case, due to the reduced tank size, only a 92% initial filling condition was analysed. Simulating a 5% initial filling as a boundary condition was not considered, as high fuel demand would result in excessively rapid liquid depletion within the tank.

Four mass flow rates—corresponding to 100%, 75%, 50%, and 25% of the maximum flow—were simulate.

As shown in [Figure 105](#), the behaviour of the storage system changes due to the lower amount of stored mass and the associated specific internal energy. In this case, higher mass flow rates result in depressurization within the tank. Specifically, for mass flow rates of 14,490 kg/h and 10,686 kg/h,

the saturation pressure achieved at total liquid depletion is lower than atmospheric pressure. This leads to a temperature decrease below the initial value, resulting in an evaporative cooling effect.

On the other hand, lower mass flow rates lead to different trends in the specific internal energy and density of the mixture, resulting in an opposite scenario, consistent with what was observed for the 20,000 m³ Type-A tank under all mass flow conditions. In fact, both saturation pressure and temperature increase throughout the simulation when 7,245 kg/h and 3,623 kg/h are considered as liquid extraction conditions. In these cases, by the end of the simulation, the pressure remains slightly higher compared to the initial value.

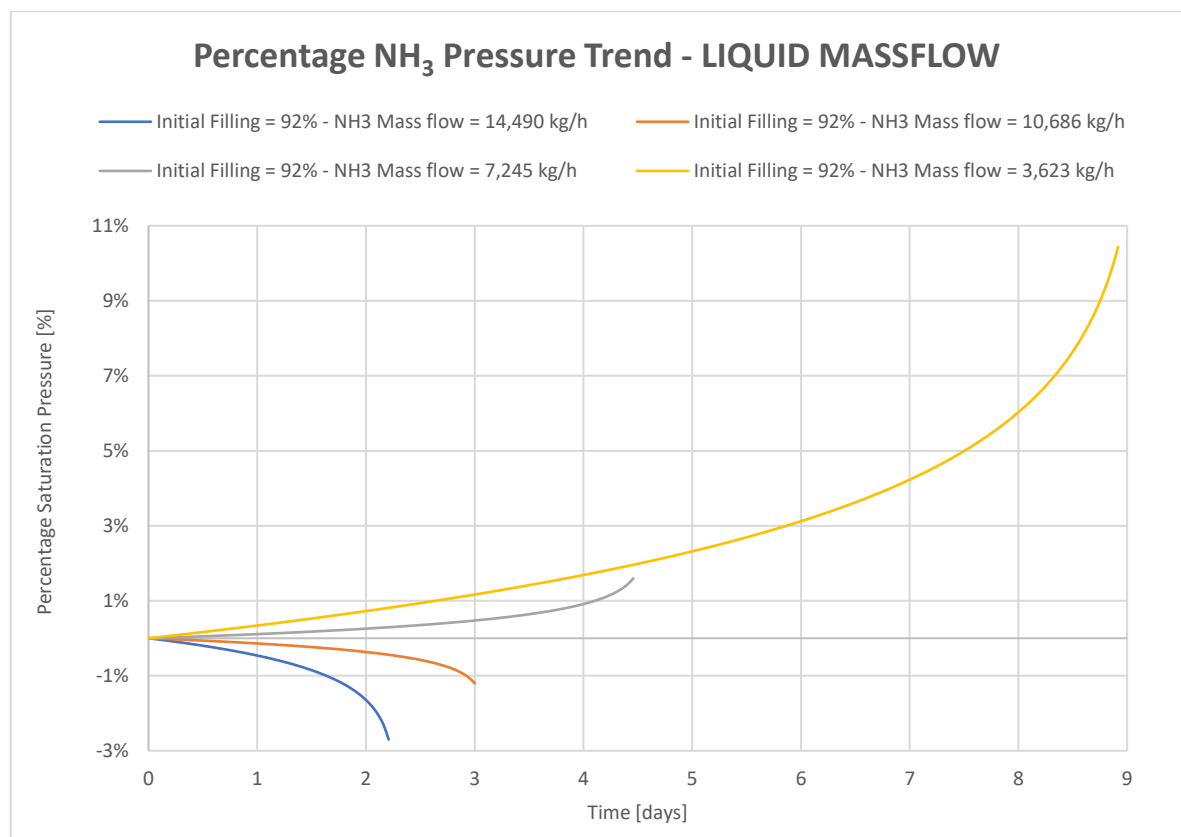


Figure 105: Saturation pressure trends for the lowest initial filling level of 92% under different sampled liquid mass flow rates

Final simulation vales obtained from this analysis are resumed in [Table 35](#).

1,250 m ³ TYPE-C TANK - MASS FLOW SIMULATION RESULTS					
Initial Filling [%]	Mass flow rate [kg/h]	Ship range [days]	Final pressure [bar(a)]	Pressure percentage difference	Final Temperature [K]
92%	14,490	≈ 2.2	0.99	-2.7 %	239.3
92%	10,686	≈ 3	1.00	-1.2 %	239.6
92%	7,245	≈ 4.5	1.03	+1.6 %	240.2
92%	3,623	≈ 8.9	1.12	+10.4 %	241.8

Table 35: Final results for the 1,250 m³ Type-C tank under different mass flow rates.

5.4. Outcomes of the Fuel Storage Analysis.

This analysis enabled the evaluation of different operational conditions through a preliminary assessment of the thermodynamic behaviour of the storage system. This was achieved by adopting a Saturated Homogeneous Model (SHM) to simulate thermodynamic progression within the tank. To ensure a high level of generalization in terms of tank geometry, fuel type, and operational conditions, the SHM was identified as the most suitable modelling approach.

As a key finding, it was observed that more detailed models, such as those belonging to the Non-Thermal Equilibrium Model (NTEM) category, proved to be too inaccurate under specific conditions when aiming to meet the aforementioned generalization requirements. While NTEM models differentiate between vapor and liquid phases and simulate their interaction through convective heat exchange, their accuracy strongly depends on case-specific experimental data. Convective heat coefficients are typically determined either experimentally or through empirical correlations based on tank geometry, fuel type, and sealed conditions, where natural convection dominates fluid movement.

However, in an onboard context—where mass flow extraction from the storage system must be simulated and where sloshing phenomena may occur—convective motion can be easily disrupted. This leads to the invalidity of the correlations, reducing the reliability of NTEM models. This effect is further amplified when storage shape and dimensions vary, highlighting a key limitation in the model's applicability.

Once an SHM was developed, case studies were conducted on a large containership and a cruise ship, each featuring different tank types and varying amounts of stored ammonia. The analysis highlighted differences in pressure and temperature evolution (both build-up and build-down) under sealed conditions and scenarios where mass flow extraction occurs.

For the containership, a 20,000 m³ Type-A tank with a MARVS of 171,325 Pa was studied under tropical conditions. Over a 50-day simulation, no significant issues were observed regarding self-pressurization in sealed conditions. However, the most critical case, requiring activation of the BOG management system, occurred at the lowest initial filling level (6%), where approximately 58.8 kg/h of gaseous ammonia needed to be reliquefied to maintain pressure within safe limits.

Regarding the cruise-ship, a 1,250 m³ Type-C bi-lobed tank was analysed under tropical conditions. Due to the design characteristics of this tank type, a MARVS of 401,325 Pa was considered. In this case, BOG processing of 7.4 kg/h was required at the lowest initial filling level (5%). Despite this, no significant issues were identified.

Considering the possibility of mass extraction and the fact that both case studies require similar mass flow rates, differences in pressure and temperature trends were observed, emphasizing the influence of the total stored mass within the tank due to its large storage capacity.

For the containership, no pressure build-down was detected when operating at the maximum flow rate (14,616 kg/h). Conversely, at lower fuel demands (3,654 kg/h), the pressure rise exceeded the MARVS, necessitating a BOG processing rate of 50.8 kg/h if the operational condition were sustained until complete liquid depletion.

For the cruise ship, the higher mass flow rates considered (14,490 kg/h and 10,686 kg/h) led to a reduction in pressure and temperature inside the storage tank, indicating evaporative cooling. However, the resulting pressure reduction—approximately 3,000 Pa—was not deemed critical in relation to potential vacuum conditions.

6. Risk Analysis: Cruise Ship as a Case Study.

Given the regulatory guidelines regarding safety and the results obtained from the storage system, the next step in detailing the ammonia application is to conduct a risk analysis on the whole fuel handling system. Due to the high toxicity of this fuel, it is crucial, as required by regulations, to understand how ammonia behaves from this perspective. A risk analysis is necessary in the "alternative design" process to ensure the same level of safety for non-conventional solutions.

This chapter focuses on a LNG-fuelled cruise ship where, due to the allocation of spaces, the entire ammonia system must be maintained in enclosed or semi-enclosed spaces, in accordance with strict safety measures. The LNG-fuelled ship baseline was selected because it more closely matches the space allocation and fuel handling system layout when compared to ammonia, making it a more economically feasible case study. The focus is on the main system components and spaces where ammonia leakage could occur. Critical issues requiring corrective actions are outlined in this chapter, along with proposed solutions.

In this scenario, the Formal Safety Assessment (FSA), as identified by the IMO, has been adopted to conduct the risk analysis. This was done in collaboration with a sufficiently large work group. The involvement of a variety of people with different expertise and experiences is a regulatory requirement, as it helps minimize the margin of error.

To finalize a preliminary assessment of ammonia onboard integration as an alternative fuel, a risk assessment has been conducted using a cruise ship as a case study, given that it represents the most stringent safety measures. In this case, an LNG-fuelled baseline has been considered to account for a more cost-effective scenario, in which either an ammonia retrofit or new-build would be implemented. This choice ensures that space allocation is already planned, and, as revealed by regulatory analysis, several safety measures and systems are already in place and compliant.

When transitioning to alternative low-flashpoint fuels, regulations mandate an 'alternative design' approach, tailored to the specific characteristics of the focused fuel. This approach requires the adoption of corrective measures to ensure the same level of safety as that achieved by existing applications. This solution, as provided by SOLAS [100] and also included within the scope of the IGF Code [69],

serves as a tool to objectively structure the decision-making process in design, particularly in cases where prescriptive regulations are either absent or not applicable. In this context, conducting a risk analysis is a mandatory step in carrying out an alternative design.

To this end, the primary document referenced for the risk assessment is the Formal Safety Assessment (FSA) [101], as defined by the IMO. This framework has been followed as a guide to conduct the study.

6.1. Formal Safety Assessment Assumptions and Overview.

Formal Safety Assessment (FSA) is defined as a structured methodology aimed at improving maritime safety, protecting life, health, the marine environment, and property through risk analysis and cost-benefit assessment [101]. Furthermore, the IMO prescribes a methodology for conducting a FSA that encompasses five distinct phases, outlined as follows.

- **Phase 1: Identification of hazards (HAZID)**

This initial phase outlines the Hazard Identification (HAZID) process, which begins once the scope of the problem is defined. The analysis requires breaking down the subject into smaller components. In the case study, this involves dividing the fuel supply system—from storage to the engine—into smaller subsystems called nodes. This method helps identify potential hazards related to the presence and operation of different system parts. Following IMO guidelines, the analysis should be conducted by a multidisciplinary team with diverse and complementary technical expertise, ensuring a thorough evaluation through varied professional perspectives.

- **Phase 2: Risk analysis**

The second phase, as affirmed by the IMO regulation, involves a detailed investigation into the causes, initial events, and consequences of the most significant scenarios identified in the preceding steps. Essentially, this phase constitutes the risk analysis itself, as it quantifies the factors determining risk, represented by the likelihood of hazard occurrence and the severity of potential damage.

- **Phase 3: Risk Control Options and Risk Control Measures (RCOs, RCMs)**

As defined by the IMO, this step aims to first identify Risk Control Measures (RCMs) and subsequently group them into a limited number of Risk Control Options (RCOs) to serve as practical regulatory strategies. The identification of RCMs involves evaluating and devising

specific actions to mitigate risk, typically by reducing either the likelihood of occurrence, the severity of potential damage, or both (e.g., installing a safety device or providing crew training). Once these concrete measures are identified, they should be consolidated into RCOs, transitioning to a higher-level framework for categorization. In this way, RCOs and RCMs provide essential insights into how risks can be mitigated and outline the practical measures that can be adopted to achieve this, respectively.

The IMO identified steps are:

1. focusing on risk areas needing control;
 2. identifying potential RCMs;
 3. evaluating the effectiveness of the RCMs in reducing risk by re-evaluating step 2;
 4. grouping RCMs into practical regulatory options.
- **Phase 4: Cost-benefit assessment**

The fourth phase involves a cost-benefit analysis aimed to compare benefits and costs associated with the implementation of each RCO. Therefore, various risk mitigation solutions are evaluated to determine which option is the most cost-effective (or least burdensome). Consequently, for conducting the risk analysis through this phase, the ALARP (As Low As Reasonably Practicable) concept, represented in *Figure 106*, assumes a crucial importance.



Figure 106: ALARP structure and philosophy

In a risk analysis, the primary objective is to minimize risk levels. However, certain measures may lead to a significant increase in costs, making them impractical. In this context, the ALARP philosophy becomes particularly relevant, as it classifies risk into different levels of acceptability, thereby enabling a balance between the costs of mitigation measures and an acceptable level of residual risk.

- **Phase 5: Recommendations for decision-making**

Finally, Phase 5 is the decision-making phase, where each option, following the ALARP analysis, is selected, allowing for the formulation of recommendations to the decision-maker.

In order to summarize the previously described FSA approach, its conceptual flow diagram is presented in [Figure 107](#).

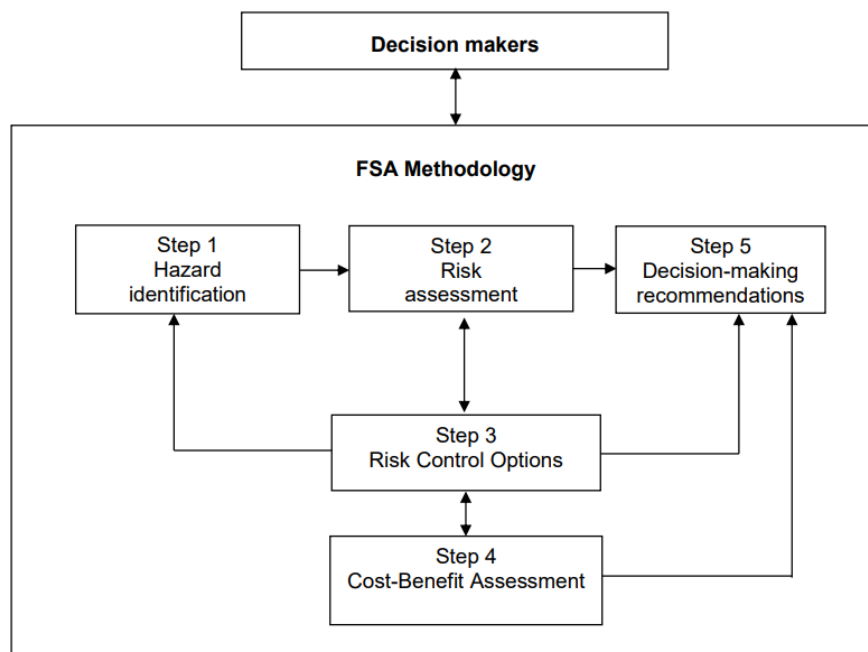


Figure 107: FSA conceptual flow diagram

6.2. Case Study FSA application.

To conduct the risk analysis for the identified case study, the previously described FSA approach was employed. Given the complexity of performing a detailed cost evaluation for the various identified RCMs, the analysis was conducted excluding the cost-benefit assessment. However, its primary objective was to provide initial detailed guidance on potential measures that could be implemented to mitigate risks on board large passenger ships. More comprehensive economic analyses would be necessary to integrate and complete the work described subsequently. The approach adopted in the analysis, in line with regulatory requirements, is illustrated in the [Figure 108](#).

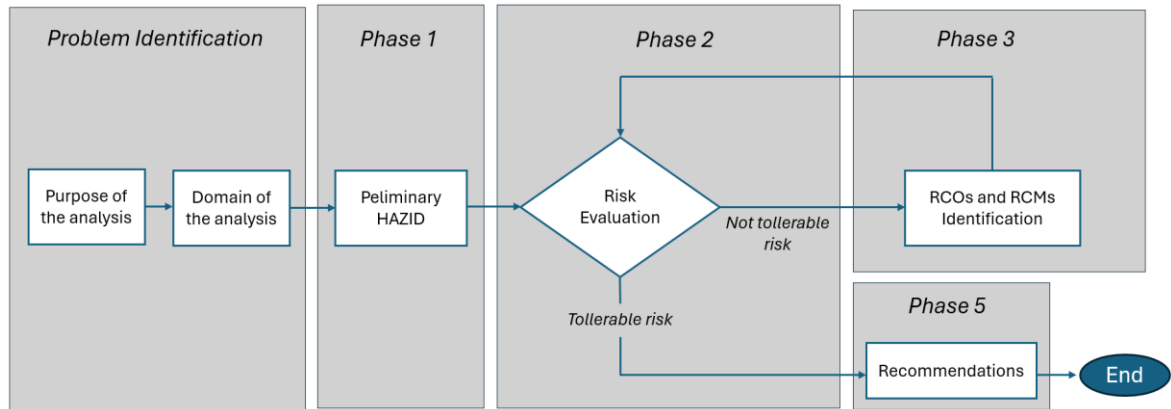


Figure 108: Risk Analysis methodology applied to the case study

6.2.1. FSA Phase 1 - Identification of hazards (HAZID).

Following Phase 1 of the FSA, a hazard identification process was conducted using prompts and guidance, namely questions or keywords designed to stimulate discussion during the HAZID. A list of sample prompts and keywords used for this case study is provided in [Table 36](#).

Prompts – Key-words
• What if the ship is involved in a collision event? • What if the ship is involved in a grounding event? • What if the space was flooded? • What if there was a fire / explosion in the space? • What if the ventilation systems shutdown? • Gas leak event • Equipment failures / Manufacturing defects / Corrosion / erosion event

Table 36: Sample of prompts and guidance used for defining the HAZID

Subsequently, coherently with the FSA, various subsystems (nodes), requiring focused attention, have been identified for modelling the whole system. The following distinction has been carried out.

6.2.1.1. Node 1 – Storage System and THS (Tank Hold Space)

For this node, the analysis has been extended to encompass two potential storage solutions. In alignment with the guidelines established by classification societies and the provisions of the IGF Code, various liquefied gas storage technologies can be employed (Type-A, Type-B, Type-C and Membrane tanks). Specifically, Type-C tanks and membrane tanks have been considered and analysed. This selection was made to provide an overview of the potential risks associated with each

technology, focusing on the one that offers the highest reliability (Type-C) and the one that could maximize storage capacity (Membrane). In fact, a membrane tank can be constructed directly on the THS structure, maximizing the utilization of the available space. *Figure 109* reports a typical cruise ship cross section highlighting both the arrangements.

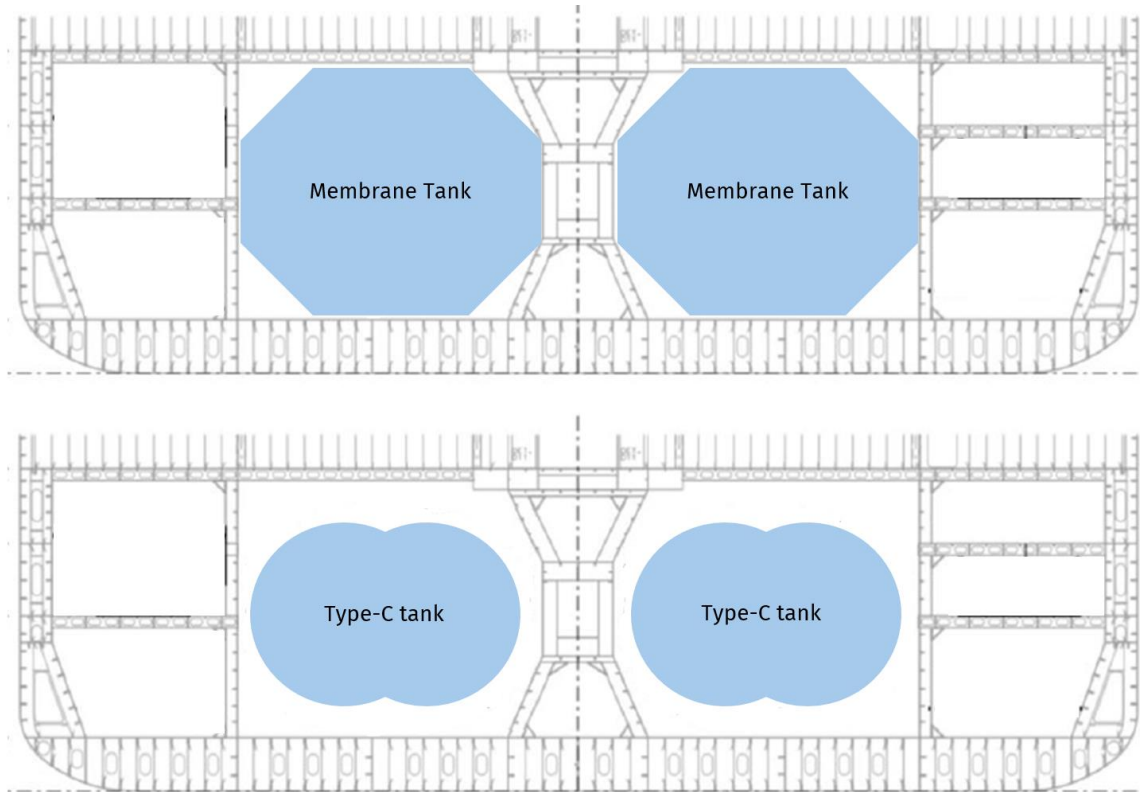


Figure 109: Typical cross-section of a cruise ship's THS, illustrating membrane and bi-lobed Type-C tank solutions

- **Type-C tank**

For this case study, two storage tanks are arranged longitudinally along the vessel and rest on two saddles within the THS. The tanks are thermally insulated and constructed with a single steel wall, designed to be compatible with ammonia and to withstand high pressures. Ammonia is stored in its liquid state at a temperature of -33°C and atmospheric pressure. Each storage tank is equipped with two PRVs with a calibration pressure of 4 bar(a), consistently with the previous assessment. The two tanks are interconnected, and each is fitted with two submerged pumps referred to as transfer pumps. Provisions are also in place for tank inerting and gas freeing to facilitate maintenance activities.

The THS is classified as a Hazardous Zone 2 area; therefore, all electrical installations within this space must be certified for use in potentially explosive environments. Ammonia

detection sensors will be installed in the area, and it is assumed that the ventilation system is operating within the THS to prevent the accumulation of toxic gases or the formation of potentially explosive atmospheres.

- **Membrane tank**

Membrane tanks are integrated tanks, as they are constructed by covering the hull structures. For this analysis, a double membrane tank has been considered (with primary and secondary barriers), although a single membrane tank could also be used for ammonia, with the hull structure serving as the secondary barrier. The choice of a double membrane system was made to enhance the segregation level, thereby improving safety. The membranes are separated by two insulation layers. According to the IGF Code definition, the space between the two barriers is referred to as the interbarrier, even if it is entirely occupied by the thermal insulation material. To meet the previous layout requirements and ensure the use of ammonia-compatible materials, the GTT NEXT1 model ([Figure 110](#)), has been considered [102].

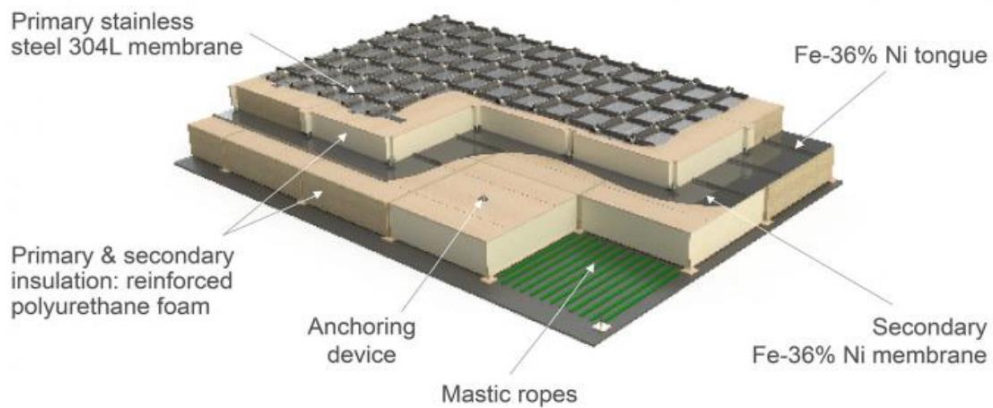


Figure 110: GTT NEXT1 double membrane tank's layout

Unlike other GTT products, this model features a primary stainless steel 304L barrier, which demonstrates good compatibility with liquid ammonia [103], as reported in [Figure 111](#).

Thomas&Betts 304 Stainless Steel Corrosion Compatibility Chart

Chemical	Compatibility	Chemical	Compatibility
Acetaldehyde	★★★★ A-Excellent	Barium Cyanide	★★★★ A-Excellent
Acetamide	★★★ B-Good	Barium Hydroxide	★★★ B-Good
Acetate Solvent	★★★★ A-Excellent	Barium Nitrate	★★★★ B-Good
Acetic Acid	★ D-Severe Effect	Barium Sulfate	★★★ B-Good
Acetic Acid 20%	★★★ B-Good	Barium Sulfide	★★★ B-Good
Acetic Acid 80%	★ D-Severe Effect	Beer	★★★★ A-Excellent
Acetic Acid, Glacial	★★ C-Fair	Beet Sugar Liquids	★★★★ A-Excellent
Acetic Anhydride	★★★ B-Good	Benzaldehyde	★★★ B-Good
Acetone	★★★★ A-Excellent	Benzene	★★★ B-Good
Acetyl Chloride (Dry)	★★★★ A-Excellent	Benzene Sulfonic Acid	★★★ B-Good
Acetylene	★★★★ A-Excellent	Benzoic Acid	★★★ B-Good
Acrylonitrile	★★★★ A-Excellent	Benzol	★★★★ A-Excellent
Adipic Acid	★★★★ A-Excellent	Benzonitrile	★ D-Severe Effect
Alcohols: Amyl	★★★★ A-Excellent	Benzyl Chloride	★★ C-Fair
Alcohols: Benzyl	★★★ B-Good	Borax (Sodium Borate)	★★★★ A-Excellent
Alcohols: Butyl	★★★★ A-Excellent	Boric Acid	★★★ B-Good
Alcohols: Diacetone	★★★★ A-Excellent	Bromine	★ D-Severe Effect
Alcohols: Ethyl	★★★★ A-Excellent	Butadiene	★★★★ A-Excellent
Alcohols: Hexyl	★★★★ A-Excellent	Butane	★★★★ A-Excellent
Alcohols: Isobutyl	★★★★ A-Excellent	Butanol (Rutyl Alcohol)	★★★★ A-Excellent
Alcohols: Isopropyl	★★★ B-Good	Butter	★★ C-Fair
Alcohols: Methyl	★★★★ A-Excellent	Buttermilk	★★★★ A-Excellent
Alcohols: Octyl	★★★★ A-Excellent	Butyl Phthalate	★★★ B-Good
Alcohols: Propyl	★★★★ A-Excellent	Butylacetate	★★★ B-Good
Aluminum Chloride	★★★ B-Good	Butylene	★★★★ A-Excellent
Aluminum Chloride 20%	★ D-Severe Effect	Butyric Acid	★★★ B-Good
Aluminum Fluoride	★ D-Severe Effect	Calcium Bisulfide	★★★ B-Good
Aluminum Hydroxide	★★★★ A-Excellent	Calcium Bisulfite	★★★ B-Good
Aluminum Nitrate	★★★★ A-Excellent	Calcium Carbonate	★★★★ A-Excellent
Aluminum Potassium Sulfate 10%	★★★★ A-Excellent	Calcium Chloride	★★ C-Fair
Aluminum Potassium Sulfate 100%	★ D-Severe Effect	Calcium Hydroxide	★★★ B-Good
Aluminum Sulfate	★★★ B-Good	Calcium Hypochlorite	★★ C-Fair
Amines	★★★★ A-Excellent	Calcium Nitrate	★★ C-Fair
Ammonia 10%	★★★★ A-Excellent	Calcium Oxide	★★★★ A-Excellent
Ammonia Nitrate	★★★★ A-Excellent	Calcium Sulfate	★★★ B-Good
Ammonia, Anhydrous	★★★★ A-Excellent	Calgon	★★★★ A-Excellent
Ammonia, Liquid	★★★ B-Good	Cane Juice	★★★★ A-Excellent

Figure 111: 304 Steel corrosion compatibility chart provided by Thomas & Bett Corporation

In the membrane tanks, liquid ammonia is stored at a temperature of -33°C and atmospheric pressure. The safety valves (two PRVs per tank) are set to a pressure of 1.7 bar (0.7 bar(g)), in accordance with the relevant regulations.

6.2.1.2. Node 2 - TCS (Tank Connection Space)

The TCS is a space located above each of the storage tanks. The TCS are liquid- and gas-tight areas, typically unmanned, with access provided through an air-lock. These spaces house all the necessary valves for ammonia transfer, safety valves, and the motors for the LP transfer pumps.

Consistently with regulations, this space is designed to provide 30 ac/h to prevent the accumulation of potentially toxic or explosive vapours. The TCS is classified as a Hazardous Zone 1 area; therefore, all electrical installations within this space must be certified for use in potentially explosive environments. The TCS is assumed to be equipped with both ammonia detection sensors and fire detection sensors (flame, heat, and smoke detectors). Furthermore, it is assumed that the space is protected by a water-based fire suppression system, which activates in the event of a fire or when ammonia is detected, in order to reduce its concentration through dilution. The water contaminated by the activation of the water mist system is assumed to be drained through various drip trays and collected in a tank with controlled venting (drain tank).

6.2.1.3. Node 3 – Bunkering System and BS (Bunker Station)

The bunkering system consists of two bunker stations located on either side of the vessel. Each bunker station is equipped with two lines connected to the tanks: one line for the intake of liquid fuel and a second line for the return of vapours. Both line connections allow for a quick disconnection in case of emergency without causing ammonia leaks (BAC). It is also assumed that bunkering can be carried out from each bunker station to both tanks. Personnel are present only during the coupling and uncoupling of the hoses, while the remainder of the operations is monitored through sensors and closed-circuit television (CCTV).

For this case study, since the vessel is a cruise ship, the bunker stations cannot be located externally falling under the definitions of semi-enclosed or enclosed spaces. Therefore, in terms of ventilation, 30 ac/h are planned to prevent the accumulation of potentially toxic or explosive vapours. Access to the bunker station will be via air-lock.

The bunker station is classified as a Hazardous Zone 1 area; therefore, all electrical installations within this space must be certified for use in potentially explosive environments.

In terms of fire detection, extinguishing systems, and ammonia leakage detection and abatement, the same measures applied to the TCS are assumed to be in place. Any water contaminated with ammonia will be directed to the same drain tank.

During bunkering operations, the receiving vessel and the supplying vessel (or terminal) will be connected through a Ship-Shore-Link (SSL) system to ensure continuous communication throughout the operations, both under normal and emergency conditions.

6.2.1.4. Node 4 - FPR (Fuel Preparation Room)

The Fuel Preparation Room (FPR) is the space where the fuel is processed before being sent to the high-pressure pump and subsequently to the engines. Like the TCS, it is a liquid- and gas-tight area, typically unmanned, with access provided via an air-lock.

The fuel flows into the FPR directly from the low-pressure pumps, which draw from the storage tanks.

An additional system present in the FPR is the BOG treatment system. For the considered case study, it is assumed that a reliquefaction plant for ammonia is employed, consisting of a compressor and a

heat exchanger. The gas generated within the tank is therefore extracted, re-liquefied, and returned to the storage tank.

In terms of ventilation, the space is designed to provide 30 air changes per hour (ac/h) to prevent the accumulation of potentially toxic or explosive vapours.

It is also assumed that two FPRs are installed on board, each connected to both tanks and all engines to maximize fuel supply flexibility. The BOG treatment system is replicated identically in both FPRs.

The FPR is classified as a Hazardous Zone 1 area; therefore, all electrical installations within this space must be certified for use in potentially explosive environments.

Similar considerations to those for the TCS and BS apply to the FPR in terms of fire detection, extinguishing systems, and ammonia leakage detection and abatement.

6.2.1.5. Node 5 - Process / Transfer to Users

Node 5 encompasses the entire piping system, extending from the TCS to the FPR and from the FPR to the engines, passing through the Engine Rooms. For this case study, as detailed in its description, it has been assumed that the fuel is directly injected in liquid form into the engines and transferred at a pressure of 18 bar(a).

Pipes carrying ammonia are double-walled when routed through areas where the presence of ammonia is not anticipated (e.g., outside the BS, TCS, and FPR).

Two solutions have been adopted for the annular space of these double-walled pipes. For all double-walled pipes located outside the Engine Room, the annular space is inerted with inert gas (N_2) at a pressure higher than that of the inner pipe (>18 bar(a)). Additionally, the annular space is equipped with pressure sensors and ammonia detectors. For the pipes located within the Engine Room, the annular space is instead assumed to be ventilated with 30 ac/h. This space is also equipped with ammonia detection sensors.

This section will also examine the buffer tank positioned on the engine. This component has been considered essential to ensure a constant fuel supply to the engine and to maintain its operation during the transition from alternative fuel to conventional fuel. Similar to the pipelines, the buffer tank is designed to withstand a pressure of at least 18 bar(a).

No specific ventilation measures are foreseen for the Engine Room, as all pipes are considered to be double-walled, thereby classifying the space as “gas safe.”

6.2.2. FSA Phase 2 - Risk analysis

Following the phase 2, described by the FSA an evaluation of different risks have been carried out.

As no statistics on accidents/failures are available for this type of system, a qualitative risk analysis was conducted. For this purpose following items have been defined and evaluated:

1. Consequences: Description of all possible consequences due to a certain hazard.

2. Effective safeguards: Description of existing safeguards. These measures can either reduce the likelihood of the general hazard occurring or mitigate the severity of the resulting damage.

3. Likelihood: Assessment of the likelihood of a given hazard occurring on a scale from 1 to 5. **Table 37** defines the likelihood levels based on occurrence frequency.

Likelihood	Definition
1 - Improbable	Unlikely to occur during the life of the ship
2 - Rare	Once during the life of the ship
3 - Unlikely	Once every five years on the ship
4 - Likely	Once a year on the ship
5 - Certain	More than once a year per ship

Table 37: Qualitative classification of likelihood

4. Severity: Evaluation of the severity of consequences associated with a given hazard. As previously mentioned, the severity of consequences was assessed across three distinct targets: human life safety—where AEGL ammonia concentration values were considered [104]—environmental impact, and power availability. This latter target has been considered in relation to the power provided by the ammonia supply system; therefore, the engine’s dual-fuel capability provides an additional redundancy that has not been factored into the risk assessment. This decision was made because the ship must be designed to meet the Safe Return to Port (SRtP) requirements, ensuring its propulsion capability under all circumstances.

Similar to likelihood, the severity is rated on a scale from 1 to 5. As shown in [Table 38](#), five levels of severity are defined in relation to the effects on the three targets.

	Persons	Environment	Power availability
1 - Insignificant	No harm to people	No environmental damage	100 % power availability
	Concentration < 5ppm		
2 - Minor	Single or minor injuries/ sickness, requiring only first aid	Minor short term environmental damage	75 % power availability
	5 < Conc. < 30 ppm		
3 -Moderate	Minor injuries/ harm, not resulting in permanent disability	Moderate impact, cleanup by internal and external resources	50 % power availability
	30 < Conc. < 220 ppm		
4 - Major	Severe injuries, permanent disability	Major impact, considerable cleanup using site and external resources.	25 % power availability
	220 < Conc. < 2700 ppm		
5 - Catastrophic	Single or multiple fatalities	Severe impact, Local species destruction and likely long recovery period, extensive cleanup	0 % power availability
	Conc. > 2700 ppm		

Table 38: Qualitative severity levels description

5. Current risk: As shown in (31), risk is defined as the product of likelihood and the severity of consequences.

$$R = L \cdot S \quad (31)$$

Where:

- R = Risk
- L = Likelihood of the hazard
- S = Severity of consequences

Given that both parameters range from 1 to 5, the resulting risk values can range from 1 to 25. [Table 39](#) shows description of different risk levels, from acceptable to totally unacceptable risks. The “Medium” level has been considered referable to the ALARP concept.

Risk ranking	Tolerance
Low	Acceptable, no immediate action required
Medium	Can be tolerable with controls documented and maintained (ALARP Concept)
High	Undesirable, control measures shall be documented and demonstrated
Extreme	Undesirable, requires consideration by senior management

Table 39: Risk ranking qualitative identification

Previous risk levels must be quantified using numerical values, determined through (31)(4). *Table 40* reports the risk ranking based on obtained numerical values.

Severity Likelihood	1	2	3	4	5
1	1	2	3	4	5
2	2	4	6	8	10
3	3	6	9	12	15
4	4	8	12	16	20
5	5	10	15	20	25

Table 40: Risk ranking assignation

6.2.3. FSA Phase 3 – RCOs and RCMs Identification

To identify the RCMs that can be adopted for reducing the risk level where necessary, an overview of all scenarios has been provided. Specifically, *Table 41*, *Table 42* and *Table 43* illustrate the number of instances in which a certain level of risk was identified. This classification was conducted for each target (human life—including personnel and guests—, environment, and power availability) and for each Node.

HUMAN LIFE (PERSONNEL and GUESTS)				
	Low	Medium	High	Extreme
Node 1.1 “Storage - FSHS Type C”	10	3	1	0
Node 1.2 “Storage - FSHS Memb.”	5	6	4	0
Node 2 “TCS”	13	7	1	0
Node 3 “Bunkering & BS”	14	13	1	0
Node 4 “FPR”	16	9	0	0
Node 5 “Process / Transfer”	11	6	2	0
GRAND TOTAL	69	44	9	0

Table 41: Risk levels frequency related with human life

ENVIRONMENT				
	Low	Medium	High	Extreme
Node 1.1 “Storage - THS Type C”	11	3	0	0
Node 1.2 “Storage - THS Memb.”	11	3	0	0
Node 2 “TCS”	19	1	1	0
Node 3 “Bunkering System & BS”	21	6	1	0
Node 4 “FPR”	24	1	0	0
Node 5 “Process / Transfer”	16	3	0	0
GRAND TOTAL	102	17	2	0

Table 42: Risk levels frequency related with environmental effects

POWER AVAILABILTY				
	Low	Medium	High	Extreme
Node 1.1 “Storage - FSHS Type C”	12	2	0	0
Node 1.2 “Storage - FSHS Memb.”	14	0	0	0
Node 2 “TCS”	20	1	0	0
Node 3 “Bunkering & BS”	26	2	0	0
Node 4 “FPR”	24	1	0	0
Node 5 “Process / Transfer”	14	5	0	0
GRAND TOTAL	110	11	0	0

Table 43: Risk levels frequency related with power availability

As a result, from the previous outcomes, it is evident that the Type-C storage technology achieves a lower average risk level compared to the membrane tank solution. This is primarily attributed to the higher reliability of the former, as highlighted in the risk assessment. Additionally, the Type-C technology, being designed to assure higher working pressures, benefits from a more robust structural integrity, fewer failure points, and improved safety features, which contribute to its overall risk reduction.

Table 44 further summarizes the overall risk frequencies per target, highlighting the fact that ammonia poses the greatest risks to personnel on board due to its significant toxicity. On the other hand, ammonia does not present particular concerns regarding environmental pollution, given its high solubility in water, which ensures rapid dispersion, as well as its zero values for Global Warming Potential (GWP) and Ozone Depletion Potential (ODP). A similar scenario is observed for power availability. This is due to the multiple redundancies in place; therefore, any potential failure can be quickly absorbed.

OVERALL RISK FREQUENCIES				
	Low	Medium	High	Extreme
PERSONNEL / GUESTS	69	44	9	0
ENVIROMENT	102	17	2	0
POWER AVILABILITY	110	11	0	0

Table 44: Overall frequencies of risk levels per target

Following previous general outcomes, criticalities realizing highest risk levels (“High” level has been considered) are reported below. For each of them it is necessary to identify potential RCMs, acting weather on severity, on likelihood, or both.

- **Ammonia vapour release from the vent mast during purging operations.**

This hazard is addressed at various points in the risk analysis. The references to the sections where this hazard has resulted in unacceptable risk levels are reported as follows.

- **Node 1.1 “Storage Type-C” – 1.11.1 “Ammonia vapors released from the vent mast during purging operations”**
- **Node 1.2 “Storage Membrane” – 1.11.1. “Ammonia vapors released from the vent mast during purging operations”**

- **Node 2 “TCS” – 2.8.4.** *“High ammonia concentration at the outlet of the purging line”*
- **Node 3 “Bunkering & BS” – 3.9.1.** *“Purging operations resulting in ammonia vapors release”*

The release of ammonia vapours from the vent mast during purging operations of fuel tanks or pipelines can lead to the formation of a toxic atmosphere in proximity of the vent mast and on the ship's exposed deck.

As a safeguard in this regard, a “toxic zone” has been established, within which access is prohibited and no ventilation inlets or other openings that could allow ammonia vapours to re-enter the ship are permitted.

The presence of such “toxic zones” (defined by most restrictive guidelines as a spherical areas with a radius of 25 m, centered at the vent mast outlet) does not, however, guarantee that ammonia concentrations outside this zone remain below established limits. BV specifies this limit as 30 ppm, consistently with the AEGL levels [104] and the Permissible Exposure Limit (PEL), defined by OSHA [105]. The PEL represents the legally permissible exposure limit to a specific toxic agent following the United States rules.

To reduce ammonia concentration at the vent mast outlet, a decision was made to integrate an air dilution system. This system can consist of a fan mounted on the vent mast, which activates during ammonia releases to ensure a high airflow rate. This increased airflow reduces ammonia concentration, ensuring it does not pose a hazard to personnel on deck.

A dispersion study, conducted through CFD simulations, is nevertheless recommended to confirm the effectiveness of this countermeasure and to quantify ammonia concentrations on the deck, considering its extremely low odour detection threshold for humans. Furthermore, such a study could serve as a basis for approving a 'toxic zone' with a smaller radius than the prescriptive 25-meter radius stipulated by current regulations.

- **Ammonia vapour release from the PRVs at the vent mast in a fire event within a membrane tank adjacent space**

Unlike the previous scenario, this hazard pertains to the release of ammonia vapours under emergency conditions. In the event of a fire in a space located near the THS, the heat flux entering the membrane tanks can increase rapidly, leading to accelerated fuel evaporation. Since storage such

as membrane tank can withstand a maximum overpressure of 0.7 bar(g), and the MARVS cannot be set to higher values, an ammonia venting event is likely to occur if this type of storage is selected. This leads to a significant amount of fuel releasing into the atmosphere surrounding the ship.

In this emergency scenario, the PRVs are considered a safeguard, as their activation due to overpressure is permitted only during fire events.

Since this hazard is comparable to the previous one, the properly designed dilution system can be adopted as an RCM. Also in this scenario, it can reduce ammonia concentration at the vent mast, thereby mitigating the severity of the consequences.

- **Release of ammonia vapours from the ventilation outlet of the double-walled pipes located in the Engine Room.**

In this case, the double-walled pipes interbarrier within the engine room, has been considered ventilated at a rate of 30 ac/hr. Since the engine room is typically located far from the THS, as is common for LNG-fuelled cruise ships, the ventilation outlet was assumed to be positioned near the engine casing outlet rather than at the vent mast. In the event of a leak from the internal pipeline, ammonia would be immediately ventilated and released in this area, creating an additional “toxic zone” not covered by the dilution system.

Since an additional dilution system is considered neither practical nor entirely effective for adequate risk reduction due to the ventilation outlet positioning, it has been determined that, in the event of an ammonia leak, the vapours can be directed to the vent mast via a dedicated line and an automatic system, which is promptly activated upon ammonia detection within the pipeline interbarrier. Similar to the dilution system, this RCM primarily acts to reduce the severity of the consequences.

- **Fire in the engine room and consequent buffer tank overpressure**

In the engine room a buffer tank for each engine is foreseen to be installed upstream the injection pump. In the event of a fire, critical issues may arise due to the temperature increase inside the buffer tank. This can easily lead to an internal overpressure with explosion risk resulting in a high risk.

For this reason, two safeguards have been proposed to mitigate the likelihood of the event. Specifically, the use of insulation material surrounding the buffer tank has been suggested, providing protection against flames for the time required to stop operations and purge the entire ammonia line. Additionally, the installation of a dedicated water spray nozzle has been considered to assist in controlling temperature increases. These measures primarily serve to eliminate the need for an

additional venting line that would require routing to the vent mast, thereby preventing further ammonia release into the environment.

6.2.4. FSA Phase 5 - Recommendations for decision-making

In line with the FSA, Phase 3 is the stage where recommendations-already reported in the previous sample tables-are formulated. These recommendations are valuable for both the plant's design and its safety. As subsequently reported, the recommendations have been categorized into three distinct groups and are identified as follows:

- **General (G):** *General recommendations for the design and construction of the plant.*
- **Layout (L):** *Specific recommendations for the plant's design and its safety.*
- **Procedural (P):** *Procedural recommendations primarily related to the operation of the plant and its effective management.*

6.3. HAZID Outcomes.

Following the risk analysis outlined earlier, it has been possible to identify the primary safety concerns associated with the implementation of ammonia as an alternative fuel aboard large passenger vessels. As anticipated, the most critical scenario concerning human safety is the potential release of ammonia, given its high toxicity. This study has facilitated a deeper exploration of this issue, enabling a detailed understanding of which specific interventions can be adopted to mitigate this risk, using a well-established baseline—a LNG-fuelled vessel—as a reference point.

Nevertheless, further in-depth studies, such as Computational Fluid Dynamics (CFD) analyses, are essential to accurately evaluate the actual severity of this hazard and the effectiveness of the proposed Risk Control Measures (RCMs). As previously noted, due to the complexity involved in cost evaluations, Phase 4 of the Formal Safety Assessment (FSA) has been excluded from the scope of this analysis, which instead focuses on the realistic proposal of RCMs. Therefore, completing this assessment remains crucial to finalize the comprehensive risk analysis.

7. Conclusions and Final Remarks

The analysis presented in this document highlights the potential of alternative fuels, specifically ammonia, as an effective means of marine decarbonization. Ammonia was chosen due to its favourable combination of high energy density, zero-carbon content, and relatively low technological complexity for onboard storage. This aligns with the growing interest in ammonia as a future marine fuel, as reflected in various projects aiming to increase global green and blue ammonia production capacity to approximately 200 million tons, based on ongoing and planned initiatives. From a request perspective, the current available order books, which include data up to 2028 and currently mainly characterized by bulk carriers and gas tankers transporting ammonia as cargo, do not show a significant increase in the production of ammonia-fuelled vessels. However, future projections estimate that the demand for ammonia as a marine fuel could exceed 300 million tons in 2050. This highlights the need to further increase the low-carbon ammonia production capacity. Perspective regarding availability of storage and bunkering means in ports still present a lack of advanced stage projects. Nonetheless first ammonia bunkering demonstration have been carried out in the port of Singapore.

The adapted multi-criteria approach, used for a preliminary comparative analysis of the suitability of ammonia as a marine fuel across different vessel types, yielded promising results, particularly for ships with shorter range requirements. A small container ship, typically operating on non-oceanic routes, and a large cruise ship, which frequently stops at ports, were two of the three case studies analysed.

When compared with other alternative fuels, ammonia performed well for these vessel types and sizes. However, extending the analysis to a large container ship requiring transatlantic range revealed that other alternatives, such as methanol or marine diesel oil (MDO), are more suitable due to their space-saving advantages.

Furthermore, the analysis highlighted the sensitivity of the comparison results to fuel price, which represents the highest share of annual operating costs. Therefore, significant uncertainty remains, depending on future fuel market scenarios and carbon penalties, such as the carbon levy.

Building upon the conducted analysis and transitioning from a general to a more detailed perspective, the simulation of ammonia storage behaviour was performed using a dedicated mathematical model developed specifically for this study. This model effectively balances generalization with a good level of detail. Based on a comprehensive literature review, the Saturated Homogeneous Model (SHM) was identified as the most suitable approach for this analysis.

Simulations were carried out for a 20,000 m³ Type-A and a 1,250 m³ Type-C storage tank, installed on board a large container ship and a cruise ship, respectively. The results of the sealed simulation indicated potential critical overpressure issues, particularly in the smaller Type-C tank when not fully pressurized, which must be effectively managed by the boil-off gas (BOG) processing system.

The mass flow extraction analysis, aligned with engine requirements, highlights the occurrence of a depressurization scenario. Notably, evaporative refrigeration takes place exclusively in the smaller tank when subjected to higher mass flow rates. However, in this context, depressurization results in slightly lower final pressure values compared to atmospheric pressure, suggesting that no particularly critical issues are expected from this standpoint. These findings indicate that smaller tanks are more susceptible to both overpressure under sealed conditions and depressurization when exposed to high flow rates.

Despite these challenges, ammonia benefits from a relatively moderate storage temperature and a high latent heat of vaporization, enabling it to absorb significant amounts of heat during phase transitions. As a result, ammonia presents fewer concerns in terms of storage pressurization compared to other cryogenic fuels, such as LNG or hydrogen. Nonetheless, as confirmed by regulatory analysis, BOG treatment systems remain a necessary requirement.

Looking ahead, future model developments are planned to extend the scope of the assessment by simulating real operational profiles characterized by fluctuating external temperatures and variable fuel mass flow demands. Additionally, the model already incorporates the capability to simulate fire events, allowing for the evaluation of potential venting scenarios. In this context, it is possible to estimate the time required for the storage tank to reach the pressure relief valve (PRV) opening threshold under high-temperature exposure, leading to a venting event. This estimated time represents a critical parameter for determining fire extinguishing response times and provides essential input for the design of fire-fighting systems aimed at protecting the Tank Hold Space (THS) and adjacent areas.

Given the toxicity of ammonia, a final risk analysis was conducted using a cruise ship as a case study. This vessel type was selected due to its stringent safety requirements, making it particularly sensitive from a risk management perspective. To establish a relevant baseline, an LNG-based case study was considered, as it already aligns well with existing ammonia-related regulatory provisions, thereby offering a cost-effective reference point. In this context, a Formal Safety Assessment (FSA), as proposed by the International Maritime Organization (IMO), was carried out to complete the risk analysis. The results align with the toxic nature of ammonia, as the most critical risks—deemed unacceptable—are associated with ammonia release within enclosed spaces and exposure in sensitive

outdoor areas. To mitigate these risks, various preventive and protective measures have been identified, aiming to reduce both the severity of potential damage and the likelihood of occurrence. Specifically, a dilution system has been deemed a feasible solution to lower ammonia concentrations when released through the vent mast. Furthermore, additional fire protection measures have been implemented to safeguard the buffer tank against potential overpressure, which could otherwise lead to ammonia leakage within the engine room.

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