D1.4 – State of the art of safety technical framework and updated risk & safety assessment and plan

Clean Hydrogen Partnership

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Acronyms

Short Acronym	Description
AMP	Alternative Maritime Power
BoP	Balance of Plant (periphery components of a fuel cell stack for processing)
BPP	Bipolar Plate (core component of a fuel cell stack)
BSI	British Standards Institution (National standards body of the UK)
CCM	Catalyst Coated Membrane (core component of a fuel cell stack)
CNG	Compressed Natural Gas
C_v	Flow Coefficient of a device (valve)
DI	De-Ionised (water) with electrical conductivity < 40 µS/cm²
DIN	Deutsche Industrie Norm, German Industry Standard (German national standadrisation body)
DIN SPEC	Deutsche Industrie Norm Specification (as successor of PAS)
FMEA	Failure Mode and Effect Analysis
FMECA	Failure Mode And Effects And Criticality Analysis
GDL	Gas diffusion layer (core component of a fuel cell stack)
GHG	Green House Gases
H_2	Hydrogen
HAZID	Hazard Identification
HAZOP	Hazard and Operability study
HFO	Heavy Fuel Oil
HT	High Temperature
HVSC	High Voltage Shore Connection
HX	Heat Exchanger
ICE	Internal Combustion Engine
ICF	International Code of Safety for Ship Using Gases or other Low-flashpoint Fuels published by the IMO
IMO	International Maritime Organization
LEL	Lower Explosive Level
LNG	Liquefied Natural Gas

LOHC	Liquid Organic Hydrogen Carrier
LT	Low Temperature
MAH	Major Accident Hazards
MARPOL	International Convention for the Prevention of Marine Pollution from Ships, 1973
MCFC	Molten Carbonate Fuel Cell
MEA	Membrane electrode assembly (core component of a fuel cell stack)
MFM	Mass flow measuring
NaCl	Sodium Chloride, sea salt
NH_3	Ammonia
NO_x	Nitrogen Oxides (refers mainly to NO, NO_2, but also N_2O_3, N_2O_4 etc.)
OCV	Open Circuit Voltage
OPS	Onshore power supply
P2A	Power to Ammonia
P2X	Power to Chemical (any)
PAFC	Phosphoric Acid Fuel Cell
PAS	Publicly Available Standard
PLC	Programmable Logic Controller
PEMFC	Polymer Electrolyte membrane Fuel Cell
PGM	Platinum Group Metals i.e., ruthenium (Ru), rhodium (Rh), palladium (Pd), osmium (Os), iridium (Ir) and platinum (Pt)
Pt	Platinum
QA	Quality Assurance
SIL	Safety Integrity Level
SoA	State-of-the-Art
SOFC	Solid Oxide Fuel Cell
SO_x	Sulphur Oxides (refers to many types of sulphur and oxygen containing compounds such as SO, SO_2, SO_3, S_7O_2, S_6O_2, S_2O_2, etc.)
UEL	Upper Explosive Level
U/I	Voltage/Current Polarisation curve

Executive Summary

The e-SHyIPS project aims to define the new guidelines for an effective introduction of hydrogen in maritime passenger transport sector and to boost its adoption within the global and EU strategies for a clean and sustainable environment, towards the accomplishment of a zero-emission maritime transport Scenario. The goal of e-SHyIPS is to move from the idea to the application, filling the existing gaps in normative and technical knowledge concerning all the related aspects on hydrogen in the maritime transport sector. By means of an ecosystemic approach, e-SHyIPS proposes theoretical pre-normative research activities on standards, simulation and laboratory experiments, design of an appropriate certification process, spot future standardization activities to enhance the EU normative and regulatory landscape.

This report presents the results of the analysis of the technical knowledge gaps and models for the risk assessment and management of gaseous and liquid hydrogen (GH2 and LH2) and alternative hydrogen-based fuels on ships, based on the state of the art previously studied. Initial methodological, technical and functional requirements based on the scenarios for ships defined in T1.1 were prepared and passed on to WP2, WP3, WP4 and WP5.

In a first step, hydrogen-based fuels for the maritime sector and suitable fuel cell types were analysed depending on the respective scenario. With literature research carried out, the functional and technical state of the art with regard to hydrogen on board and for fuel cells was first defined in a comprehensive statement not only focussed on the maritime sector. These requirements were defined in close cooperation with partners from the maritime industry: In the previous report 1.1, use cases for ship design were defined and the technical and functional requirements for passenger ships with hydrogen-based fuels were elicited in operating scenarios.

In a second step, the current legal framework, PAS and safety methods were examined in more detail. As a result, knowledge gaps were identified in detail and proposals were made to address them. Thus, technical knowledge gaps and models for risk assessment and risk management of gaseous and liquid hydrogen (GH2 and LH2) and alternative hydrogen-based fuels on ships were identified and described.

The underlying structure of the project shows a close interconnection of the subtasks in WP1 as well as all work packages among each other. Therefore, the knowledge gained here flows directly into the ongoing work of these WPs.

1. Introduction

Over the last decade, environmental sustainability has become a priority policy concern the development of freight and passenger transport. In maritime transport, low-carbon shipping and tackling air pollution are seen as priorities: Exhaust emissions from ships into the atmosphere and seawater are harmful to the marine ecosystem as well as to human health, increase acid rain and contribute to global warming.

Although international shipping is already the most energy-efficient form of bulk transport (Wang & Lutsey, 2013), a global approach is needed to further improve energy efficiency and effectively control emissions.

According to the third IMO THG study, depending on future economic and energy policy developments, an increase in CO_2 emissions from international maritime transport is expected to result in a 50-250 % increase in CO_2 emissions by 2050. For this reason, the IMO (International Maritime Organisation) published the MARPOL (MARine POLlution) Annex for Maritime Transport in 2011. (MARine POLlution) Annex VI to prevent pollution from ships in order to reduce CO_2, NO_x and SO_x levels. Three years later, in 2014, the EU Commission adopted the Alternative Fuels Infrastructure Directive 2014/94 [1], which established a common framework for the development of alternative fuels infrastructure in the Union.

The main objectives were to reduce dependence on oil and mitigate the environmental impact of transport. The directive sets minimum requirements for the development of alternative fuels infrastructure, including refuelling stations for natural gas (LNG and CNG) and hydrogen, with common technical specifications.

1.1 Scope and Objectives

This report describes the activities of Task 1.4 of Work Package 1.

This task was carried out with the objective to review technological framework state of the art in terms of available hydrogen-based fuels and alternative fuels and their application on passenger ships, fuel cell technologies and capabilities.

Therefore, task T1.4 reviews Publicly Available Specifications (PAS) and Technical Specifications (TS) used by ISO and IEC.

Additionally, the identification of technical knowledge gaps and models for risk assessment and risk management of gaseous and liquid hydrogen (GH2 and LH2) and hydrogen-based alternative fuels on ships was carried out and is described in this Deliverable.

1.2 Methodology

The following approach was chosen for the identification of the necessary investigations. First, it had to be worked out which system components are used in principle for the use of hydrogen fuel cells in maritime applications. In parallel, the influence of the expected environmental conditions on the individual components must be worked out. These environmental conditions naturally vary significantly from the intended area of application: in particular, harmful gases in the media supplied are a potential source of damage and/or reduction of the service life of fuel cells. On this basis, a matrix of the materials and components to be tested and the conditions to be applied has to be developed and described in test plans.

1.3 Connection with Other Deliverables

This D1.4 "State of the art of safety technical framework and updated risk & safety assessment and plan" refers specifically to all tasks of WP1, especially T4.2 and T4.3 of WP4, and serves as input for:

- D1.3 "State of the art of the safety standardisation framework"

In addition, the initial requirements in T1.1 for scenario definition are reviewed and forwarded to WP2, WP3, WP4 and WP5.

2. Technology Framework State-of-the-Art – Fuels for Passenger Ships

2.1 Analysis of the current political and legal framework conditions

The main objectives of the measures described in relation to the policy and regulatory framework were to reduce dependence on oil and mitigate the environmental impact of transport. The Directive sets minimum requirements for the development of alternative fuels infrastructure, including refuelling stations for natural gas (LNG and CNG) and hydrogen, with common technical specifications. In addition, the IMO adopted a first decarbonisation strategy in 2018 to reduce greenhouse gas emissions from ships by 2050.

The strategy includes all measures that are continuously implemented by IMO to reduce emissions from international shipping through the adoption of mandatory technical and operational energy efficiency and environmental performance measures. In response to the need to mitigate the risks associated with climate change, the strategy has set a target to reduce overall emissions by 50% by 2050 compared to 2009. The strategy is under continuous review, with a review scheduled by 2023.

In 2015, the EU Sulphur Directive 2012/33/EU [2] set a drastic reduction in sulphur emissions from all ships operating in the Baltic Sea, the North Sea and the English Channel. This limits sulphur emissions (mainly SO_x) to 0.1% by 2020, or alternative solutions must be introduced that achieve an equivalent effect. For regular passenger ferries in the EU, the sulphur limit outside ECAs is 1.5% by 2020. The above reduction in SO_x emissions is expected to have an impact on fuel prices, which means additional costs for the shipping industry. For passenger ferry services, this means higher operating costs and consequently higher fares for passengers. Furthermore, compliance with NO_x and SO_x requirements can prove very costly (DNV, 2014). For this reason, specific policy mechanisms and incentives have been promoted by the EU to drive Europe's transition to a low-carbon economy. In addition, as of 2018, the IMO is adopting a first strategy to reduce GHG emissions from ships (reducing total annual GHG emissions by at least 50% by 2050), which takes a dual approach:

Establishing a regulatory framework and promoting the market, supported by capacity building initiatives.

This first strategy aims to:

- (i) take urgent action to address climate change and its impacts and strengthen IMO's contribution to the global effort by addressing GHG emissions from international shipping,
- (ii) identify measures to be implemented by the international maritime sector; and
- (iii) identify actions and measures that contribute to achieving the above objectives, including incentives for research.

This first strategy is the first milestone in the roadmap for the development of a comprehensive IMO strategy to reduce greenhouse gas emissions from ships, to be launched in 2023. Hydrogen (H_2) and fuel cell (FC) technologies can play an important role in Europe's new energy system for the maritime sector. Therefore, the INTERIM GUIDELINES FOR THE SAFETY OF SHIPS USING FUEL CELL POWER INSTALLATIONS [3] are a significant step forward.

> *"1 The Maritime Safety Committee, at its 105th session (20 to 29 April 2022), having considered a proposal by the Sub-Committee on Carriage of Cargoes and Containers, at its seventh session, recognizing the importance of providing criteria for the arrangement and installation of fuel cell power installations on board ships so as to provide at least the same level of safety and reliability as new and comparable conventional oil-fuelled main and auxiliary machinery installations, approved the Interim guidelines for the safety of ships using fuel cell power installations, as set out in the annex.*
>
> *2 Member States are invited to bring the Interim Guidelines to the attention of shipbuilders, manufacturers, shipowners, ship managers, masters and ship crews, bareboat charterers and all other parties concerned.*
>
> *3 Member States are invited to recount their experience gained through the use of these Interim Guidelines to the Organization, for the Committee to keep them under review."* Citation from the introduction.

The findings and conclusions of this preliminary guide have been incorporated into the present document and are adopted in full and discussed in the following chapters.

However, H_2 and FC technologies for the maritime sector and ship design are neither covered nor supported by further specific regulatory framework. Although some case studies of hydrogen-powered ships and yachts are already on the market, the lack of specific regulations for the maritime sector undermines the uncertainty of shipbuilders' investments in these technologies. The current approach to ship design and arrangements for H_2-based fuels, materials, components and safety engineering on board and for bunkering relies on the general IMO 'Alternative Design' procedure, which requires systems to be demonstrated to be equivalent to conventional power generation systems in terms of safety, reliability and dependability.

This approach lacks early risk management in all design and operational aspects, including general ship and systems engineering, bunkering procedures and logistics interface, and power generation and management safety systems. Going beyond the state of the art, although there are already international regulations for marine engine systems that run on alternative fuels, an appropriate normative framework for the use of hydrogen-based fuel systems on board ships and yachts needs to be developed. Through its ecosystem approach and methodology, e-SHyIPS will draw both on external knowledge from current policies, regulations and standards, also thanks to its links with the IMO, interaction with the Advisory Board and networking with other stakeholders and initiatives, and on the new data emerging from its internal activities and experiments. By combining these two bodies of knowledge, e-SHyIPS will create a knowledge base that will store the structured and unstructured information needed to review and update the regulatory framework for the development of a pre-standardisation plan for:

(i) the design guidelines,
(ii) the integration of fuel cell energy systems into the ship's network,
(iii) the requirements for the interaction of ships in ports and at berth, and
(iv) safety and risk management, considering on-board systems, operational and human aspects. The references contained in the plan may be adopted or listed by the technical and standardisation bodies and IMO committees.

2.2 Comparison of different maritime fuels and energy sources

In the scientific community, the possible alternative fuels and also the comparison with fossil-based conventional fuels have been intensively investigated, and thus some very detailed publications with related discussions are available [4].

In summary it can be concluded that not only the different fuels but also the pathways to their production/generation need to be considered holistically in terms of cost and especially environmental impact. An overview on several relevant

Hydrogen (both, LH2 and GH2), while requiring the most energy to produce, also have the highest gravimetric energy content and do not cause carbon and particulate emissions; different pathways are also possible for their production; each alternative pathway has strengths and weaknesses, so the available data provides important guidance for fuel selection and stakeholder decision-making in decarbonising the maritime sector.

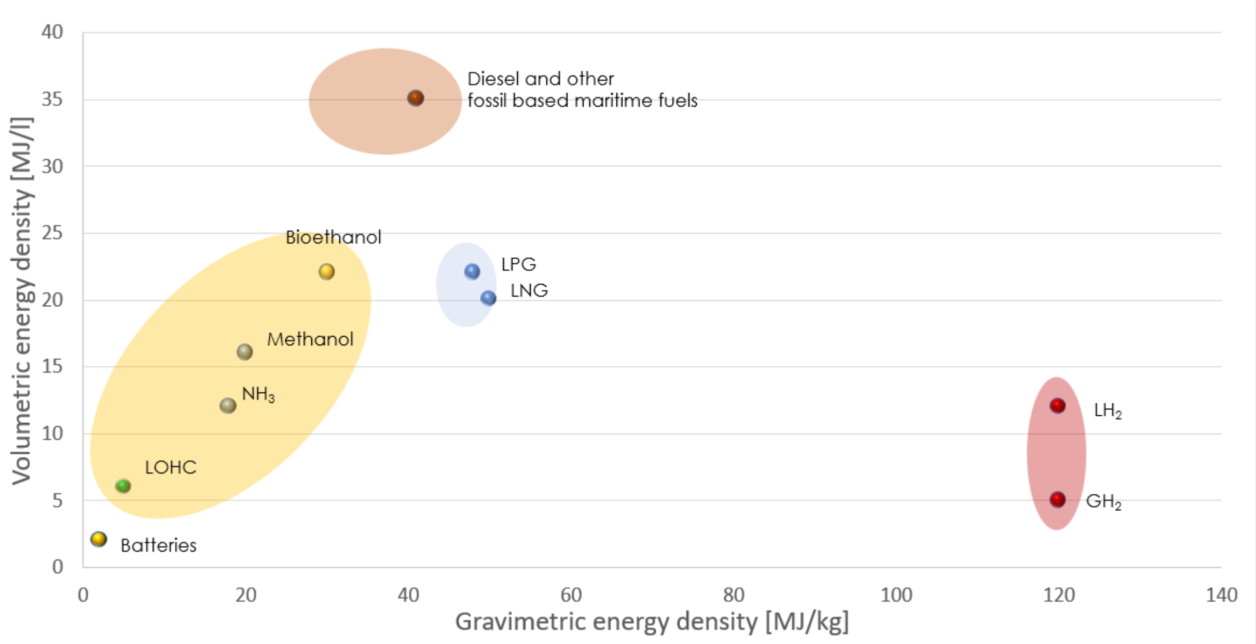


Figure 1: Overview on typical maritime fuels and energy sources

The e-SHyIPS project itself will only focus on hydrogen as a promising and uncompromising solution in terms of climate and environmental performance as defined at the proposal stage of the project.

At the same time, it has to be emphasised that ammonia (NH_3) and Liquid Organic Hydrogen Carriers (LOHC) have also become a topic in the discussion on possible climate-neutral fuels, especially for high-energy demand applications [5], [6], [7]. This has changed significantly since the project application and the start of the project. Especially the advantages of NH_3 are obvious, as storage is much easier (higher boiling point, easy to liquefy). The production of NH_3 from H_2 as a basic chemical is also carried out over very long and well-optimised processes on a large industrial scale via Haber-Bosch process [8] and is known as power-to-ammonia (P2A) or power-to-x (P2X) respectively. Nevertheless, the production of NH_3 costs about 30% of the primary energy of H_2, so that the overall efficiency is significantly lower, and the hazards of this substance is also much higher than with pure H_2: the heating value and hence the energy density is significantly lower (see Figure 1) and NH_3 is toxic, corrosive, flammable/explosive [9], [10].

Due to the changed framework conditions since the project application, the consortium discussed in detail whether NH_3 should be considered as a hydrogen carrier. The decision, also taking into account the opinion of the EU Commission (PO), was made in such a way that the focus of the e-SHyIPS project is clearly and only on H_2 and NH_3 is not considered.

2.3 Overview on Hydrogen Storage Systems

For reasons of limited space and weight requirements, the fuel should generally have both a high calorific value and a high energy density per volume in all mobility-related applications. Under standard conditions, the fossil fuels commonly used in the maritime sector, such as diesel or heavy fuel oil (HFO), have the advantage of being in a liquid state, which optimises storage volume and avoids the refueling/bunkering and off-take concerns associated with compressed gases. (As with most other mobile applications, of course).

Therefore, hydrogen storage methods are a crucial element for the use of this fuel in transport. For this reason, great efforts are being made to technically optimise the possibilities of H_2 storage and to overcome the existing challenges. The following Figure 2 shows an overview of the technologies currently under discussion. Hydrogen storage can basically be divided into two different categories: physical storage technologies, in which the hydrogen is compressed and/or cooled, and storage technologies based on materials in which the hydrogen is chemically or physically absorbed[11]].

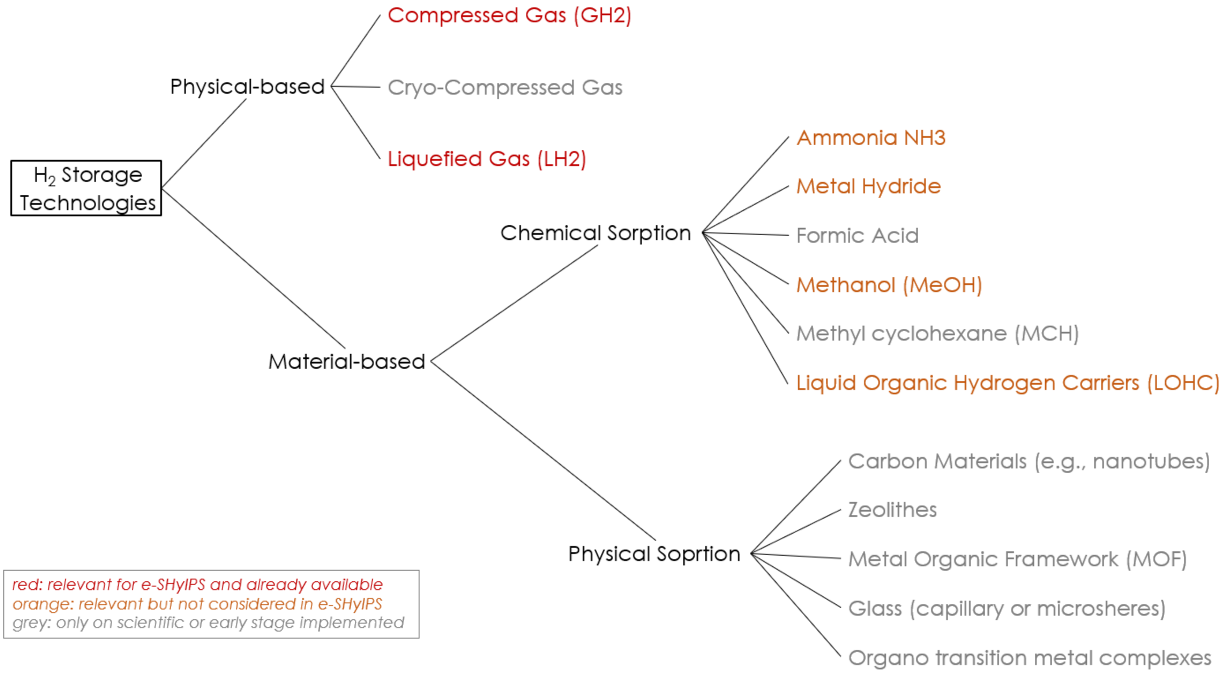


Figure 2: Overview on potential and available Hydrogen storage technologies

A rough assessment of the potential H_2 storage technologies in relation to maritime applications is also given in the form of the colour highlighting (see legend Figure 2).

As already mentioned, weight is an important design parameter in the maritime sector, as in all mobile applications. In addition to the weight of the H_2 carried, the weight of the actual tank is of course also essential. To evaluate the performance of a tank, we introduce the gravimetric ratio, which is defined as the ratio between the weight of the hydrogen on board and the weight of the full tank or, more general, the storage solution:

$$Gravimetric\ ratio = \frac{Weight_{H2}}{Weight_{H2} + Weight_{storage}} \qquad [1]$$

In a study on the economic and climatic impact of hydrogen in aviation, where this requirement is definitely the highest, a gravimetric ratio of 35% is targeted [12], [13], in order to justify the structural effort involved in transporting very large quantities of hydrogen. Of the two principal storage types presented, physical storage solutions offer the highest gravimetric ratios [14].

The idea is to choose the conditions for hydrogen storage in such a way that the density of hydrogen is increased and thus its occupied volume is reduced. This is possible:

(i) increase the pressure of the hydrogen in gaseous form, leading to GH2,
(ii) decrease the temperature of the hydrogen, leading to LH2,
(iii) Combination of both-Cryo-compressed CcH2.

Although an intermediate solution of so-called cryo-compressed technology is possible and is currently being investigated [15], [16], [17], [18] this method is not yet commercially available on a large scale and is therefore not discussed in detail in the e-SHyIPS project.

In general, however, this method, like the other storage technologies described, is more or less suitable and its further development should be observed in the future after the end of the project.

H_2 gas (GH2) storage technology

Since the introduction of the first high-pressure hydrogen tanks in the late 19th century, the design of high-pressure tanks has gone through several types of technology, each more weight and volume efficient than the last.

Typically, the following types are differentiated, with advantages and disadvantages inherent to each system [19]:

Type I: A traditional steel cylinder for storing gases for industrial processes. Inexpensive to manufacture, but very heavy. In the form of conventional gas cylinders (e.g., 200 bar/300 bar, 50 L) [20], [21]), this type is present on the market and, in the configuration of exchangeable cylinder bundles, can also be a suitable and, above all, cost-efficient solution for maritime applications, provided that the required hydrogen or energy demand is manageable and a rapid exchange of cylinder bundles (e.g., in a containerised solution) is necessary or meaningful.

Type II: An additional carbon fibre reinforcement surrounds the inner steel tank and holds the load together with the metal. This makes the tank more resilient and lighter, but also more expensive than Type I.

Type III: A carbon fibre tank with an inner steel or aluminium liner. The outer carbon fibre container holds the load. Since more carbon fibre is used, the costs are higher than for type II, but higher pressures can be achieved.

Type IV: A carbon fibre container with an inner liner made of plastic (polyamide or polyethylene). Type IV tanks cost more to purchase but are distinguished from all other tank types by their significantly lower weight and very high load capacity.

Therefore, this technology is considered the best choice for applications with the highest demands for low weight of the overall solution.

This linerless tank technology is often referred to as **Type V** and is currently under development.

The following illustration in Figure 3 shows an example of a TYPE IV storage tank. It should be noted that, for safety reasons, most pressure tanks are equipped with TPRD (Thermally Activated Pressure Relief Device) protection. This means that a pressure relief valve opens as soon as a critical temperature occurs. However, in the actual implementation, especially with larger tank systems, attention must be paid to the exact position of this TPRD or the equipment with several TPRDs in one tank [22].

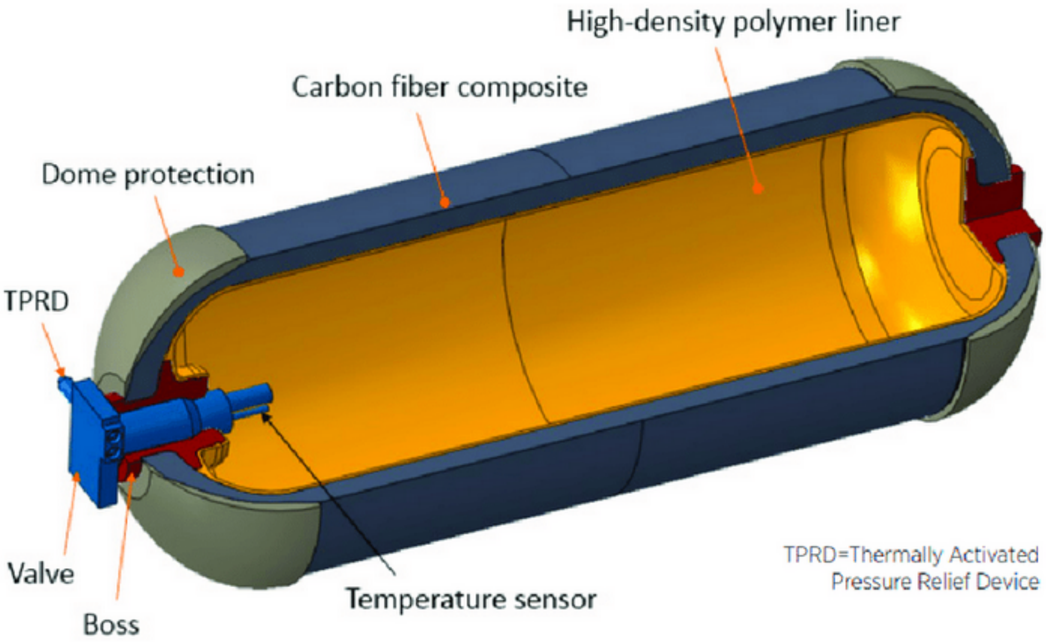


Figure 3: Type IV composite overwrapped hydrogen pressure vessel (source: Process Modelling Group, Nuclear Engineering Division. Argonne National Lab (ANL). Reprinted from [23] Copyright DOE 2017.

Liquid H2 (LH2) storage technology

The density of liquid hydrogen LH2 is 70.99 g/l. In addition, H_2 makes up 11.2 % of the weight of water. Its melting point is -259.125 °C and its boiling point -252.88 °C [24], [25]. 2.8 kg of petrol or even 2.1 kg of natural gas contain as much energy as 1 kg of H_2 if considered the lower calorific value. In other words, given its properties, H_2 has the highest mass-related energy density among common fuels. The volume-related energy density of LH2 is only about $^1/_3$ that of natural gas and ¼ that of petrol.

The technological challenges with liquid hydrogen are related to temperature. At low temperatures, as with most substances and materials, the chemical and mechanical properties of H_2 and the materials used for liquid storage change significantly. Below the glass transition temperature, plastics and polymers lose their elasticity and these are no longer ductile but become very brittle. Therefore, most polymers cannot be used in liquid hydrogen tanks. Metals are also subject to cold embrittlement at cryogenic temperatures, so materials must be carefully selected with weight in mind and are usually metal alloys such as stainless steel, aluminium, copper, brass and monel. Of these, stainless steel is most commonly used for cryogenic applications, but for weight reasons aluminium (and its alloys) represents a more suitable solution for hydrogen storage tank material. Specifically, low-density alloys such as Al-Li, which offer lower density and higher modulus of elasticity than standard aluminium alloys [10]. Some of them, such as alloy "8090", have a density as low as 2.54 kg/dm^3, almost 10% lighter than conventional aluminium alloys (2.66 - 2.84 kg/dm^3) [26], but quality improvements in composition and processes still need to be made before we can produce materials that meet the regulations for such critical applications as aerospace.

The next challenge is to minimise heat transfer. The liquid state of liquid hydrogen is only reached at a cryogenic temperature of about 19 K. The heat that is transferred from outside the tank is not transferred.

The heat coming from outside the tank vaporises the liquid hydrogen into a gas that must be vented and released, used or re-liquefied to avoid overpressure in the tanks, which are normally only designed for low pressures below 10 bar. The key technology in liquid hydrogen storage is, of course, insulation.

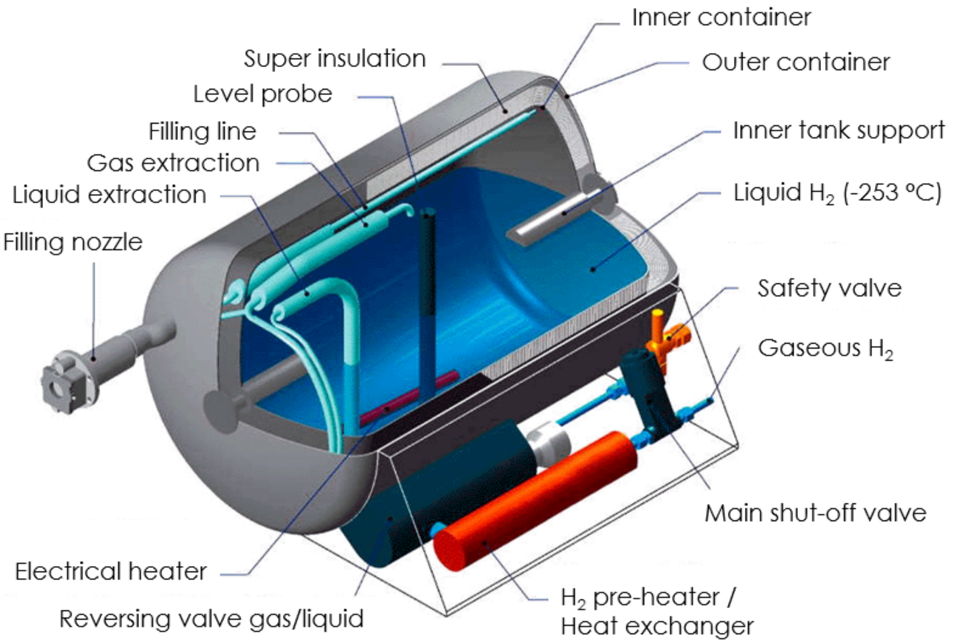
The minimisation of all three modes of heat transfer (conduction, convection, and radiation) should be addressed by using materials with low thermal conductivity, low emissivity at heat and low mobility fluids (vacuum).

Multi-layer insulation is a well-suited solution, as it consists of a series of metal sheets that impede radiation transmission and are separated by a low conductivity filler material that is under extremely low pressure (typically <1 Pa) to reduce convection.

Aerogels, which are gels where the liquid part has been replaced by gas, making them a lightweight and porous material, are also good candidates. Silica aerogels can be as light as 3 kg/m^3 because the solid is only about 10% of the volume, the rest being gas trapped in nanopores. This reduces conductive and convective transmissions, and under normal conditions the apparent conductivity can be up to 30 mW/(m·K) and up to 13 mW/(m·K) in soft vacuum [27].

It is notable that surface-to-volume ratios are critical in insulation, and in this respect larger, spherical tanks offer a major advantage. With the advancement of low conductivity materials, such as aerogels, small to medium sized liquid hydrogen tanks (<300 m^3) could have low heat flux (1 W/m^2) without the need for high vacuum [28].

The following illustration in Figure 3 shows an example of a liquid hydrogen storage tank system [29].



Source: www.Linde.com

Figure 4: Design schematic of (heavy duty) liquid H_2 storage tank system

Although cryogenic hydrogen tanks have long been used in aerospace applications, one of the major drawbacks is that the fatigue behaviour of these tanks is unknown. This is because the tanks installed in launch vehicles are designed for single use only. In the Genesis application, however, the tank is filled and emptied many times, so the mechanical and thermal fatigue behaviour of the tank is an important criterion that must be taken into account.

One way to optimise the weight of the liquid hydrogen tank is to use a composite wall instead of aluminum alloy. This is also currently under development.

General Overview on Hydrogen Properties and related Safety Concerns

All fuels inherently carry some degree of hazard. The safe use of fuels is about avoiding situations where the three combustion factors - ignition source (sparks or heat), oxidant (air) and fuel - are present. Once the specific properties of the fuel in question are known, fuel management systems can be designed with appropriate engineering controls and guidelines can be established for the safe handling and use of a fuel.

A number of properties of hydrogen [23], [24] make it safer to handle and use than most the (fossil based) fuels in common use today. H_2 is a non-toxic gas that has neither colour nor odour. Moreover, hydrogen does not pose a cancer risk and is not self-igniting. With a density of 0.0899 g/l (0°C), hydrogen is about 14 times lighter than air. Due to its high diffusion speed, it spreads quickly in all directions and mixes rapidly with air.

Some of the specific properties of H_2 require additional engineering controls to enable its safe use. H_2 is highly flammable. It is also important to keep H_2 away from sources of ignition and to take measures against electrostatic charging. Complications can arise if high concentrations are inhaled - but this is due to the lack of oxygen (O_2). The complications range from movement disorders to unconsciousness to the danger of suffocation.

In particular, H_2 has a wide range of flammable concentrations (LEL: 4.0 Vol-% H_2 in air; UEL: 75.0 Vol-% H_2 in air) [30] and a lower ignition energy than petrol or natural gas, which means it can ignite more easily. Therefore, proper ventilation and leak detection are important elements in the design of safe hydrogen systems. Because hydrogen burns with an almost invisible flame, special flame detectors are required.

In addition, some metals can become brittle when exposed to hydrogen, so the selection of appropriate materials is important in the design of safe hydrogen systems. In addition to developing safety features in hydrogen systems, training in the safe use of hydrogen is a key element in ensuring its safe use. In addition, hydrogen system tests - tank leak tests, garage leak simulations and hydrogen tank drop tests - demonstrate that hydrogen can be produced, stored, and dispensed safely.

In the following sections, the concrete risks based on H_2 (general aspects, in gaseous storage GH2 and in liquid storage LH2) are discussed:

Common concerns for Hydrogen (both, LH2 and GH2)

Based on the general properties of hydrogen independent of the state of aggregation, the following risks are to be considered:

- Develop relevant hazardous (EX) zones for hydrogen
- Explosion risk for releases into confined space
- Jet fire and flashfire (often invisible)
- Ignition source control
- Material embrittlement
- Risk of autoignition when burst discs are used
- Dimensioning of safety relief valves (higher capacity required than for LNG)
- Ignition of hydrogen in case of release through the vent mast
- Use of inertised spaces to reduce explosion risks
- Asphyxiation hazard
- Limits accessibility

Specific concerns for Liquefied Hydrogen (LH2)

In addition, there are a number of hazards that emanate from storage in the form of liquid hydrogen LH2:

- Release of LH2 into enclosed spaces
- Pressure build-up due to rapid vaporization
- Low temperature effect on equipment
- Explosion of oxygen-enriched condensed air and LH2
- Loss of vacuum in cryogenic storage tanks
- Excessive boil-off discharge/pressure build-up in tank
- Sloshing in tank
- Loss of tank pressure
- Inerting issues
- Condensation and solidification of nitrogen
- Condensation and solidification of oxygen
- Safe arrangement of tank connection space

- Dense gas behaviour for LH2-releases, e.g., through gas mast or during bunkering
- BLEVE (Boiling Liquid Expanding Vapour Explosion), LH2 trapped in confined volumes

Specific concerns for compressed Gaseous Hydrogen (GH2)

H_2 storage in gaseous form (GH2) also bears certain risks, mainly depending on the pressure level of the gas storage system.

- Release of GH2
- Pressure (including pressure-peaking phenomenon)
- Ignition mechanisms
- The high pressure is a hazard on its own
- Catastrophic failure of GH2 composite tanks due to impact, fire or deterioration due to fast-filling.

In summary, it can be concluded that depending on the respective storage conditions, a range of H_2-specific risks can occur. These are largely known and there are a number of measures that can successfully mitigate the risks discussed. This is described in detail in the following chapters and the corresponding work packages of the e-SHyIPS project on risk assessment.

As more H_2 demonstration projects and applications (both on land and at maritime environments) are conducted, the safety record of hydrogen can grow and build confidence that hydrogen can be as safe as today's widely used fuels.

3. Technology Framework State-of-the-Art – Fuel Cell Technologies for Passenger Ships

Considering the energy requirements on board ships, in principle two/three different application cases can be envisaged:

a) Propulsion

b) Auxiliary Power Supply

c) Cold Ironing (also called Alternative Maritime Power (AMP), Shore Power, High Voltage Shore Connection (HVSC) or Onshore power supply (OPS)

The respective implementations may vary very little with regard to the fuel cell systems. Only the energy demand / power class provided can be significantly different. In this deliverable, the focus is on the application <u>on-board</u> a ship to cover the full energy demand, i.e., propulsion and auxiliary consumers and hotel load.

3.1 General overview on fuel cell types and applicable fuels

As described before the term "Fuel Cells" in general covers several types, which differ significantly in their performance classes, lifetimes, operating strategies/parameters and other parameters. For a variety of reasons, however, not all of them can be usefully employed in the intended areas of application on board ships.

The following section takes a closer look at the most common fuel cell technologies and their TRLs, as well as their specific relevance to applications in the maritime sector:

The best candidates for operation on board of a vessel:

- PEMFC (LT or HT) low - mid power demand hydrogen (LT), reformate (HT)
- SOFC mid to high power demand reformate operation possible
- MCFC high power demand reformate operation possible

Also possible in principle:

- PAFC reformate operation possible
- DMFC very low power demand methanol

Probably not preferred / not suitable:

- AFC, most of the other types

The following Table 1 provides an overview on relevant and meaningful fuel cell technologies and assessment regarding their suitability in the maritime sector

FC Type	**Fuel**	**Operating Temp.**	**Pro**	**Contra**
AFC	H2	≤ 80 °C	Dynamic operation Start/Stop capability High el. efficiency Emission free	High H2 purity High O2 purity Low lifetime
PEMFC	H2	≤ 80 °C (LT-PEM)	Dynamic operation Start/Stop capability High el. efficiency High lifetime Emission free	High H2 purity
PAFC	Reformate	≤ 200 °C	Low H_2 & O_2 purity requirement	Low dynamic operation Start/stop capability Low el. efficiency Low lifetime Emissions
MCFC	Reformate	≤ 650 °C		
SOFC	Reformate	≤ 1000 °C	Low H_2 & O_2 purity requirement High lifetime High el. efficiency	Low dynamic operation Start/stop capability Emissions

Table 1: Typical Fuel cell types with selected key parameters

3.2 Definition of three typical maritime scenarios for fuel cells application

The aim of WP2 was to present the functional and technical e-SHyIPS requirements and to produce a draft of the preliminary technical specifications as also detailed in the associated deliverables D2.1.

Based on the work carried out, a set of requirements was then collected and investigated and three scenarios were developed, each with a different profile, to structure the framework conditions of fuel cells on board ships:

- SCENARIO S - The small scenario vessel refers to small ferries that are mainly used in inland waters, such as river crossings and river cruises, which provide their customers with regular daily public transport service in lagoon or fjord areas where, due to the morphology of the area, daily transport mainly takes place on inland waterways. The reference vessel is the waterbus 2407, built by the Dutch shipyard ad project partner Damen and primarily delivered to water-based public transport companies to provide passengers with urban mobility on inland waterways;

- SCENARIO M - Medium-size scenario vessel refers to medium-size ferries that operate mainly as operated as ROPAX (roll-on/roll-off passenger). This acronym stands for vessels with roll-on and roll-off functions for the carriage of commercial vehicles and private cars with the possibility to carry a large number of passengers separately for shorter journeys. As these vessels have functions that contain a mixture of passengers and cargo, they must comply with a number of strict safety and technical parameters. The reference vessels for this scenario are part of the project partner Levante Ferries fleet;
- SCENARIO L - Large scenario vessel refers to luxury cruise ships of small/medium length that are characterised by a high level of service and a large number of services for the passengers. The reference project for this scenario definition is Celebrity Cruise's the newest ship named Flora, entered service in 2019.

A rough overview can be found in the following Table 2, detailed information on the respective classes and how they were developed can be found in *D2.1 - Functional and Technical Requirements for Scenario Report Definition*

Scenario	**S - Waterbus**	**M - RoPax**	**L - Cruise**
Energy demand [kWh]	776 (one roundtrip)	28’660 (sailing) 10’589 (at berth)	54’465 (max one day) 210’850 (max four days)
Power demand [kW]	650	7’200	7’050
Fuel Cell Technologies	PEMFC (SOFC)	PEMFC (SOFC, MCFC, PAFC)	PEMFC (SOFC, MCFC, PAFC)
Hydrogen Carrier/Storage	GH2	LH2	LH2 (LOHC, NH_3, other)
Hydrogen storage demand [kg]	375 (one day)	2’300 (one day)	9’288 LH2 (four days autonomy)

Table 2: Energy demands, fuel cell types and hydrogen storage for the three scenarios

3.3 Typical components of FCs for ship applications

The following figure shows a typical block diagram of a fuel cell with its structural units of the system independent of the specific type. The centre of the system is the fuel cell stack with the respective supply units for the necessary media (Balance of Plant). The general PEMFC design used in the e-SHyIPS project as presented and discussed in the previous deliverables (e.g., D4.1 – *Selection of materials and components for experimental testing and test plan*) is also applied in this deliverable. For this reason, the details discussed here will only be briefly described.

Generic P&I diagram

In order to be universally valid and independent of the manufacturing process, a generic model from the U.S. Department of Energy (DOE) was chosen as the basis for the PEMFC system design [31]. This is shown in the following Figure 5[1].

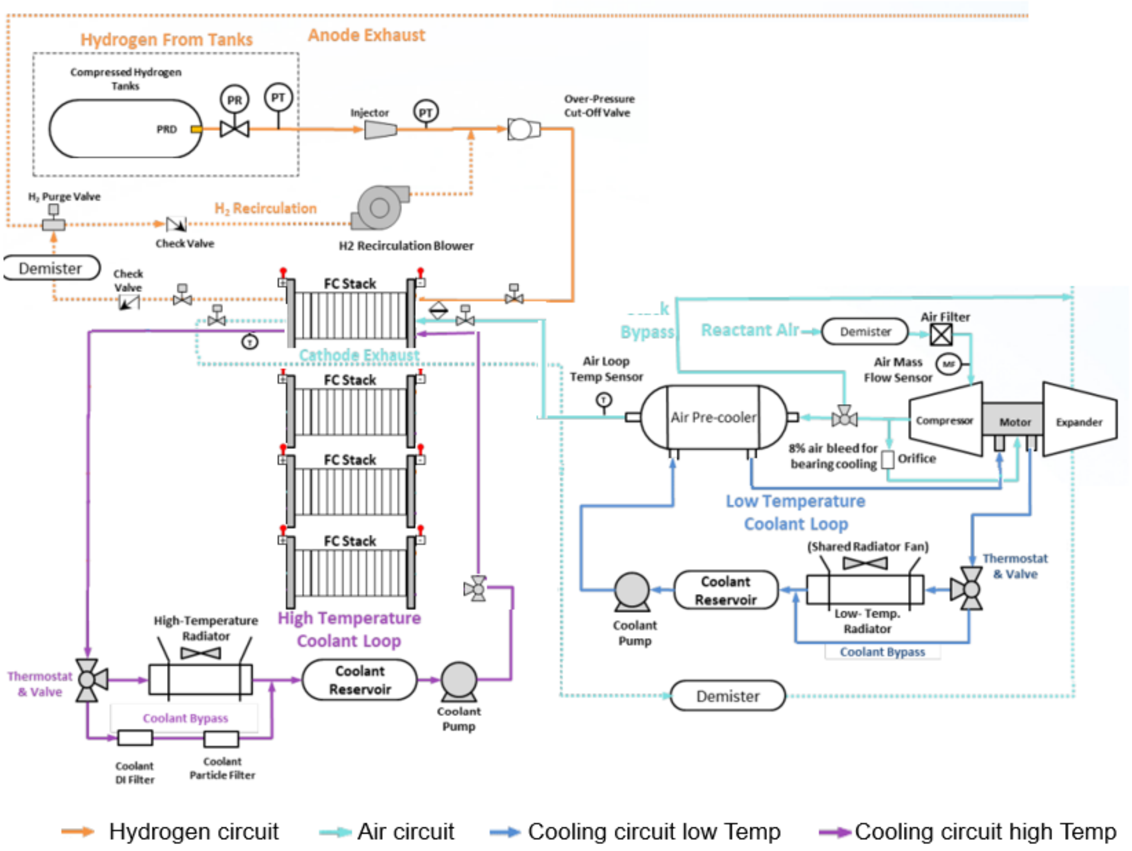


Figure 5: Exemplary heavy duty PEMFC P&ID from DOE 2021

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[1] Remark: The H_2 tank and supply system is not in scope although depicted for clarity.

The media lines are shown as an example for one fuel cell stack but can also be adapted at the level of several stacks (4 stacks are exemplarily shown here).

Interfaces

For the discussion it is necessary to define the interfaces between the individual components and modules investigated in scope of the e-SHyIPS project. These are depicted in the block diagram shown in Figure 6.

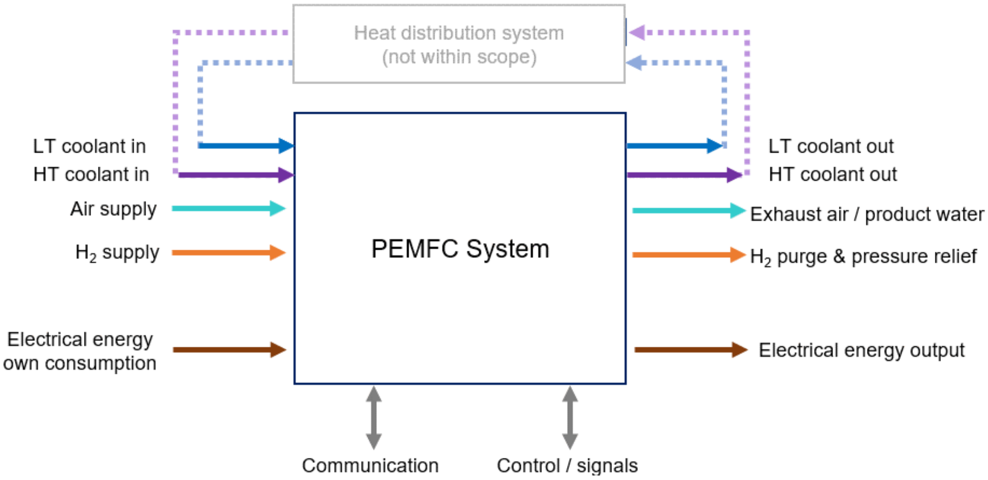

Figure 6: PEMFC system block diagram with interfaces to the superordinated system

Details of these interfaces can be found in the following Table 3.

Interface	**Guiding from / to**	**Remark**
Air supply	Ambient	Air filter included in the FC system
H_2 supply	H_2 supply system / storage tank	
Exhaust air /product water	Ambient	
H_2 purge & pressure relief	Ambient / safe area	Depending on the safety strategy (ATEX Zone)
Communication	Master control	
Control /signals	Master control	
LT coolant in	LT Coolant system / radiator	Can be used for heating purposes (batteries, passenger cabin etc.) Both, LT and HT cooling circuits, may also be realised in one single circuit
LT coolant out		
HT coolant in	HT Coolant system / radiator	
HT coolant out		

El. energy supply (own consumption)	DC/DC link	For start-up in operation this energy consumption will be supplied by product energy
Energy output	DC/DC converters	Also not considered here in detail

Table 3: Interface description of typical fuel cell systems on board of vessels

3.4 Fuel cell system concept and basic safety strategy

For the e-SHyIPS project, a typical approach for a fuel cell installation on board a ship was designed. To obtain a scenario that is independent of the ship size and supplier, the fuel cell modules or systems were planned as a multi-module concept, where the required energy demand can be tailored by parallelising the individual modules. This gives a large degree of freedom with regard to the interpretation of the scenario, and one is not limited to a concrete concept of a manufacturer.

The concept discussed was originally designed for PEM (LT-PEM) fuel cells. However, even if this approach is generally applicable to all fuel cells, adaptations in detail may be necessary for other fuel cell types such as SOFC, MCFC, etc.

Specifically, the following detailed considerations are based on the maritime systems of the project partner Proton Motor as an example. However, the assumptions apply in a similar way to fuel cell systems in general and are transferable to systems from other manufacturers.

The basic fuel cell design concept and safety strategy considerations are:

- The fuel cells are located in a separate fuel cell room (separate from electrical equipment, engines, hydrogen storage, battery storage, etc.).
- Within the fuel cell compartment, the fuel cell stack itself and all hydrogen-containing elements are housed in a separate gas-tight cabinet. This fuel cell cabinet must be equipped with forced air and monitoring air. Monitoring the exhaust air flow with a redundant arrangement of flow sensors and hydrogen detectors is elementary to the basic safety strategy.
- All non-hydrogen peripheral components of the Balance-of-Plant (BoP) can be housed directly in the fuel cell room (possibly in cabinets or racks).
- The fuel cell room is not force-ventilated during normal operation. Since there is no hydrogen installation (except for the tightly mounted double-walled hydrogen-carrying pipes), it is not required for safety reasons.

However, it must be ensured at all times that a sufficient amount of process air can flow freely and unhindered to the supply air modules (interfaces are the air filters).

The statements made here refer to one fuel cell room or one fuel cell module. This means that in the case of parallelisation for several systems, a concept can be developed in which the unsafe systems and rooms can be switched off, but redundant systems without safety problems can continue to run undisturbed if necessary and thus continue to ensure the ship's energy supply. In addition, hybridisation with batteries in the sense of a redundant energy supply can serve a similar purpose.

3.5 Technical Scope / Components and Modules

The following components and subsystems are subject of this investigation:

Hydrogen subsystem

Most LT-PEM fuel cell systems are only approved for operation with pure hydrogen gas. Any hydrogen storage and tank system can be provided to supply the fuel cell system with hydrogen. As long as the hydrogen quality can be guaranteed according to the FCS supplier specification, no restrictions result from the combination of PEM fuel cells with different hydrogen supply solutions. For Installations of SOFC, MCFC or other HT fuel cells the H_2 quality is not so crucial and other H_2 sources (including syngas and indirect H_2 carriers such as natural gas or other hydrocarbon-based fuels) can be utilised[2].

For fuel cell stacks with an output of up to 60 kW (net power), the minimum pressure requirement for hydrogen is currently 2 to 3 bar(g). Typically, fuel cell stacks can be operated with an inlet pressure of 7 to 10 bar(g).

Air supply subsystem

The Fuel cell system sucks air out of the surrounding area. The air sucked in is filtered by the air supply subsystem of the FCS. The standard PM air inlet filter module is made for “normal” air. For special requirements, like salty air in harbour environment or off-shore conditions, there is maybe a special filter-technology needed.

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[2] Note: as those fuels do not correspond to pure hydrogen in terms of climate-friendly and sustainable energy supply, they are not considered in the context of the e-SHyIPS project.

The intended air supply unit (mainly consisting of air filter, air compressor and intercooler) must be placed inside the fuel cell compartment, but outside the fuel cell cabinet, as it does not have a hydrogen line.

Cooling subsystem

The basis of the control of fuel cell systems is commonly an exact control of the thermal conditions within the fuel cell. For this purpose, a cooling system consisting of a coupled small and large primary cooling circuit with control by a mixing valve is part of the fuel cell control strategy. The primary cooling circuit under the control of the fuel cell is independent of the secondary cooling system.

Reaction gas exhaust

Both, anode and cathode side of fuel cells usually produce a certain amount of gaseous exhausts. The reaction exhaust air of a fuel cell system is fed together with the anode exhaust gas (purge gas) into a common exhaust gas interface.

Some basic conditions must be observed for the exhaust air duct or exhaust gas section with outlet to atmosphere. The integration of the vessel must fulfil the requirements of the routing of the exhaust gas lines into the application accordingly.

- The common hydrogen purge gas and reaction exhaust air interface must lead into an area defined as EX Zone 1 according to ATEX.
- The exhaust gas lines must also be defined "internally" as areas with potentially explosive atmospheres ("internally": within the media lines).
- Potential ignition sources/electrical components must not be integrated into the exhaust gas lines.
- Exhaust lines must be designed and selected with regard to electrostatic charging (material selection; earthing, etc.).
- The cross-sections of the exhaust pipes and lines in relation to the drainage openings must be sufficiently dimensioned.
- By the heat input of the discharged and warm reaction air (in operation) a freezing of water within the exhaust pipes is prevented (enable thermal bridges by suitable choice of material; use insulation material around the pipes).

Reaction water exhaust

The cathode (air) section contains a condensate drain for draining the liquid components of the product water in the reaction exhaust air. The water produced on the cathode during the operation of the fuel cell is largely gaseous at the operating temperature but condenses due to cooling when leaving the fuel cell stack and in the further exhaust air duct, since the cathode exhaust air is almost saturated with water vapour. The resulting condensed product water is discharged from the system via the interface. Some basic conditions must be observed:

- In PEMFC technology, the (product) water is produced on the cathode side by the chemical reaction. Since the membrane has a high water permeability and the operating temperatures are usually well below 100 °C, liquid product water has to be discharged at both the cathode and the anode. This water is usually collected by means of condensate drains in the exhaust pipes centrally at the lowest point of the pipe routing and must be able to flow away unhindered via the drain openings, interface.
- In principle, care must be taken to ensure that the media lines run downwards towards the separator! Due to the falling pipe routing and the position of the steam trap at the lowest point as well as the shutdown procedure, draining pipes should also be strongly falling and dimensioned as short as possible in order to prevent complete "freezing over" at standstill.

For the drain of the product water several things have to be observed:

- Fuel cell product water is pure water and can be guided into the environment but also may stored in a tank[3]. Both is possible.
- The water exhaust must be located below the lowest point of the fuel cell system. Otherwise, a pumping system is necessary.
- Depending on the operating point, large quantities of product water are produced from the fuel cell system. The tank volume must be designed sufficiently to be able to collect the product water quantity during the entire operating phase.
- Under no circumstances must water flow back into the fuel cell system.

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[3] Although not toxic, it is not appropriate for use as drinking water (at least not without appropriate elaborate treatment).

- Material must be suitable for DI-water (corrosivity!) and must be suitable for hot media (theoretically up to 70 °C, but most likely much lower temperature).
- The solubility of hydrogen in water is very low; for water the solubility of H_2 is 19.4 ml/l (1.6 mg/l) at 20 °C and normal pressure. However, as failsafe measure it is recommended to vent an optional tank into a safe area. Further measures (hydrogen sensor) may be taken into account.

Ventilation and forced air system

The ventilation concept with a suitable ventilation system is an integral part of the safety strategy.

As an essential factor in the safety concept, the fuel cell cabinet in the fuel cell room is force-ventilated at a high flow rate. A fan is located in the inlet of the cabinet in the lower area. The outlet is via the roof of the cabinet into a safe area.

In addition, both the fuel cell cabin (one hydrogen detector) and the fuel cell compartment (multiple hydrogen detectors) must be monitored. These hydrogen sensors are integrated into a safety chain via the ship's master control unit. If a limit concentration of hydrogen in the ambient air (usually between 10 to 40 % LEL[4]) is exceeded, the fuel cell system is stopped immediately and driven to a safe state (all hydrogen supply lines closed and vented, all other valves opened, electrical connections disconnected). If the alarm is triggered in the fuel cell room (not in the fuel cell cabinet), the forced ventilation of the cabinet is stopped immediately and another ventilation system in the fuel cell room ensures that the hydrogen is quickly diluted and removed. In this case, too, all supply lines must be closed off.

Materials and components

The selected materials have to be extensively tested in maritime systems and, if available, are approved for use in this application to meet all requirements. The materials used and the installed components do not pose any hazard or danger. No toxic, irritating or corrosive substances are released or used. Typically, only the cooling

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[4] Especially at lower H_2 concentrations, it is not unusual to trigger a pre-alarm beforehand and, if necessary, initiate appropriate measures.

circuit contains a (relatively uncritical), fuel cell-compatible and approved cooling medium based on ethylene glycol.

3.6 Fuel Cell System Safety Concept

A safety concept has to be developed on the basis of experience with fuel cell systems and a risk assessment carried out for all operating conditions with an experienced, multi-disciplinary team. Exemplary safety measures as listed in this document result from a typical hazard and risk assessment at the consortium partner Proton Motor.

Hydrogen safety strategy

For the maritime fuel cell system, a safety concept was elaborated as combination of measures from vessel manufacturer (installation rooms and venting) and fuel cell supplier (fuel cell safety concept).

All hydrogen containing elements of the fuel cell system such as fuel cell stack modules, their anode loops and the exhaust system are enclosed in a cabinet with a forced air ventilation for avoiding explosive atmospheres in any case. The amount of air required for this has to be calculated on the individual conditions (free space, maximum leakage/H_2-release rates etc.). The maximum amount of hydrogen that can be released corresponds to the maximum amount of hydrogen that is fed into the system from the hydrogen storage tank via the hydrogen interface 3/2-way solenoid valve at the system inlet. The maximum flow rate that can be achieved is given by the C_v value[5] of this valve.

The volume flow of the forced air is monitored, supervised by hydrogen sensors and directed to a safe area according to the ATEX directive (2014/34/EU)[32] by explosion protected blowers:

A potentially explosive atmosphere according ATEX is a place in which hazardous explosive atmospheres may occur in such quantities as to require measures to protect workers from explosion hazards. Such a quantity is referred to as a hazardous explosive atmosphere. As a basis for assessing the extent of protective measures, remaining potentially explosive atmospheres must be divided into zones according to the

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[5] The flow coefficient C_v of a device (valve) is a relative measure of its efficiency at allowing fluid flow. It describes the relationship between the pressure drop across an orifice valve or other assembly and the corresponding flow rate. (source: Wikipedia)

probability of the occurrence of hazardous explosive atmospheres. Examples for installation on ships are given according [3].

Zone 0: A place in which an explosive atmosphere consisting of a mixture of air and flammable substances in the form of gas, vapour or mist is present continuously or for long periods or frequently. On ships this is relevant for: interiors of tanks, reformers, pipes and equipment containing low-flashpoint fuel or reformed fuel, any pipework of pressure relief or other venting.

Zone 1: A place in which an explosive atmosphere consisting of a mixture of air and flammable substances in the form of gas, vapour or mist is likely to occur in normal operation occasionally. On ships this is relevant for the fuel cell compartments and in a defined distance of air exhaust and gas outlets or venting pipes etc..

Zone 2: A place in which an explosive atmosphere consisting of a mixture of air and flammable substances in the form of gas, vapour or mist is not likely to occur in normal operation but, if it does occur, will persist for a short period only. These are on-board of ships mainly the surroundings of zone 1 and e.g., airlocks.

All non-hydrogen components of the fuel cell systems such as cathodic air supply unit (air filters, compressors, intercoolers etc.) and parts of the cooling loop (pumps, heat exchangers etc.) are to be located in the fuel cell room outside the cabinet. This fuel cell room is not forced vented in normal operation but will be in case of a failure of the fuel cell cabinet forced air ventilation.

Fuel cell cabinet and fuel cell room are supervised by several hydrogen detectors and fire detectors. Additionally, a fire extinguishing system is built-in the fuel cell room.

Safety logic

The controller can control or regulate the process plant via the sensors (analogue & digital) and actuators used as well as the control units used. The control system is thus able to record, check and finally switch off the operating status at any time. In any condition outside the specified limits of the monitored parameters (pressure, temperature, H_2 concentration), the fuel cell system is converted to a safe state by the fuel cell control, FCC.

- A shutdown occurs when:

  - non-operational system states occur (e.g., at malfunctions of components)
  - the corresponding limits are exceeded
  - Triggering sensors or control units with switching functions
  - Malfunctions of the control unit occur (watchdog)
- On the controller there is a safety logic that is independent of the application software that regulates and controls the system. This safety logic can switch off certain safety-relevant outputs (output groups) in the event of an error, independent of the application software, and thus put the system in a safe state.
- The regulation and control of the fuel cell system by the application software together with the monitoring by the independent safety logic ensures that the system is operated exclusively within a permissible operating window.

Danger from explosive atmospheres

- During operation, no explosive atmosphere can occur in the direct vicinity of the system modules. This is ensured by a combination of a technically gas tight system and natural ventilation.
- If the natural ventilation is not sufficient due to the installation situation, measures have to be taken, such as forced ventilation (if possible), or an additional hydrogen sensor must be used in this area.
- The definition "technically gas tight" is achieved through routine leakage tests, regular service checks and the use of suitable materials and components.
- Within the stack module, the argumentation as a technically sealed system cannot be made because the fuel cell stack has a system-related hydrogen leakage. This leakage is very small and may be considered less than 5 l/min. For guiding this hydrogen into a safe area, a nozzle is built in the stack module housing. A small hose ducts this line to the hydrogen sensor in the forced air outlet. Due to the high dilution with the force air stream, no explosive atmosphere can arise. To avoid explosive atmospheres, additionally permanent monitoring by a hydrogen sensor is therefore carried out.

- As part of the fuel cell quality assurance, a leak test is carried out for each stack before commissioning according ISO DIN EN 62282-2. During this test both internal and external leak rates are measured. This test ensure that the leak rate is less than 5 cm^3/min. No higher leak rates are allowed.
- The exhaust media ducts are designed to guide the exhaust air (oxygen depleted) and anode purge gas (containing hydrogen). The exhaust air flow and purge flow are designed in such a way that sufficient dilution of the purge hydrogen is guaranteed at all times. This duct is guided into an ATEX zone (e.g., trunks, lances etc.).
- Additionally, a hydrogen sensor monitors hydrogen concentration and will detect a higher concentration of hydrogen in case of a failure to initiate appropriate measures (brings systems into a safe state).
- Hydrogen sensors between stack module and water separator can detect a failure and ensures that there is no explosive atmosphere possible in this line. With the water separator itself hydrogen would be guided into the common exhaust line leading to the ATEX Zone at the end.

Thermal / Mechanical / Electrical hazard

- A possible overheating of the fuel cell stack is indirectly detected or monitored via a temperature sensor in the exhaust gas flow of the air. The measured temperature leads to a switch-off at a threshold of ≥75 °C. The temperature is then measured at a threshold of ≥75 °C.
- Electronic components and drives have their own temperature monitoring and thus protect the components intrinsically safe from damage due to overheating.
- The heater used for the frost start is monitored by an integrated temperature switch. If a defined temperature threshold is exceeded, the heating supply is switched off. The heater used is intrinsically safe due to its technology. The heating only takes place in a heating routine provided for this purpose before the actual system start and is otherwise not active.
- All potentially hot surfaces are marked accordingly and should in principle be inaccessible to the user after integration.
- The anode circuit with a maximum working pressure of 0.9 bar(g) is protected at the pressure level of 1 to 1.1 bar(g) by means of a pressure switch and a pressure sensor with evaluation in the safety logic.

- Neither the coolant pump used, nor the air compressor should be able to generate large pressures within the air and cooling section. The components used within these sections are suitable for this pressure stage.
- Electrical safety is ensured by constructive protective measures such as touch protection or insulation of live parts as well as overcurrent protection devices. Mechanical covers with regard to touch protection can only be removed by using tools. All components that are placed outside an enclosure or units that have transfer interfaces have corresponding electrical protection classes.

Fire extinguishing system

Typically, a suitable fire alarm system must be implemented to monitor the fuel cell room. This also meets the requirements resulting from the fuel cell system risk assessment. For the fuel cell room, a fire extinguishing system must be considered that meets the overall maritime requirements on-board of ships.

3.7 Dimensions, Volume and Weight of an exemplary Fuel Cell System

Table 4 below shows the dimensions, volumes and weights of the components and subsystems as they apply to Proton Motor's typical maritime systems design approach.

Table 4: Volume and weight of cabinets, components and subsystems

Component	**Dimensions [mm x mm x mm]**	**Volume [l]**	**Weight [kg]**	**Quantity in scenario**		
				S	**M**	**L**
FC Cabinet equipped (without media)	1800 x 900 x 400	648	500	6	68	55
Periphery cabinet equipped (without media)	920 x 830 x 700	490	400	12	136	110
Total system	**n.a.**	**1200**	**900**	**6**	**68**	**55**

The following Figure 7**Figure 7** show the two compartments of a typical maritime fuel cell system HyShip® of the project partner Proton Motor, which was selected as an exemplary basis for these investigations. These modules were divided into a periphery cabinet without any H_2 containing components (behind) and a separate fuel cell cabinet (in front), containing two fuel cell stacks with all hydrogen containing components in a gas-tight enclosure (the housing is not depicted here). The enclosure of the fuel cell cabinet includes two of the fuel cell compartments stacks on top of each other equipped with a forced ventilation and supervised via redundant H_2 detectors and air flow sensors.

Figure 7: Picture of the exemplary fuel cell system HyShip® from Proton Motor

Especially for the higher performance requirements of the scenarios "M" and "L", this existing solution described here would not be very advantageous. In a concrete application, optimising the packaging would lead to a significant reduction in the required construction space.

Another advantage of the modular approach is the possibility of distributing the energy supply units to different rooms, since, comparable to diesel-electric operation, no mechanical connection to the drive motors is required. This also makes the redundant design much easier to realise. However, there may be a higher cost in terms of safety technology.

4. Publicly Available Standards

4.1 Publicly Available Specification (PAS)

A Publicly Available Specification (PAS) is a standardisation document that is very similar in structure and format to a formal standard but has a different development model [33].

The development of a PAS must not conflict with existing standards or standards in the drafting stage and must complement and not contradict legislation in the relevant field. It shall also be written in accordance with the standardization body drafting rules, which means that the content shall be technically sound and not technically restricted (i.e., it shall not contain patented or proprietary methods or products). It is written clearly and with objectively verifiable requirements or recommendations [34].

The aim of a publicly available specification is to speed up the standardisation process. PAS are often produced in response to an urgent market need.

A PAS is a public requirement, but not yet a standard. However, its publication by the German Institute for Standardisation (DIN) gives it a special weight. The main differences to a ISO/DIN standard are as follows:

(i) A PAS is an agreement among the drafters - without ensuring social consensus - as a standard requires.
(ii) It is faster and less expensive than adopting a standard. Publication takes place just six weeks after the final text is submitted to ISO/DIN. A standardisation process takes several years.
(iii) In contrast to a standard, the responsibility for the content of the PAS does not lie with ISO/DIN, but with the authors.

Furthermore, also the BSI Group pioneered the PAS format and develops PAS in the UK,[1] while the International Electrotechnical Commission develops international PAS in the field of electrical, electronic and related technologies, and the International Organisation for Standardisation develops international ISO PAS [35].

4.2 DIN SPEC

From the German national standardization body DIN the successors to the PAS are the DIN specifications (DIN SPEC) introduced in 2009. The currently valid PAS will be retained until they are withdrawn.

DIN SPEC (PAS) is a consortium standard that is developed within a few months in small agile working groups and is not subject to consensus. The German standardization organization DIN ensures that a DIN SPEC (PAS) does not contradict existing norms and standards. The standards can also be published internationally and also be the basis for a DIN standard.

Currently, DIN has 152 ongoing and published DIN SPEC according to the PAS procedure. The range of topics includes, for example, terminology, classification, measurement, testing, procedure and interface standards, guides or reference architecture models on the various innovative topics. The initiators of the standards come from the manufacturing industry, the service sector or from science; they include large companies as well as start-ups and SMEs.

4.3 PAS in context of Fuel Cells and Hydrogen in maritime applications

One of the tasks of the task was to summarise and evaluate the relevant PAS.

However, especially with regard to hydrogen and fuel cells in general and also in the maritime context, this research did not prove to be very fruitful. No PAS were identified in the narrow context, and only very few relevant PAS were identified in the broader context of the topic.

PAS 79: Fire risk assessment – Guidance and a recommended methodology [36]

This PAS gives guidance and corresponding examples of documentation for undertaking, and recording the significant findings of, fire risk assessments in buildings and parts of buildings for which fire risk assessments are required by legislation.

PAS 2060: Specification for the demonstration of carbon neutrality [37]

Carbon neutrality means not adding new greenhouse gas (GHG) emissions to the atmosphere. Where emissions continue, they must be offset by absorbing an equivalent amount from the atmosphere, for example through carbon capture and reforestation that is supported by carbon credit schemes.

PAS 4444:2020: Hydrogen-fired gas appliances. Guide Withdrawn!

The Department for Business, Energy and Industrial Strategy (BEIS) has set up the Hy4Heat Research and Innovation Programme. The PAS has been written primarily to support this programme but could also form the basis for wide-scale standardization of hydrogen-fuelled appliances by providing principles for manufacturers regarding the safety and functionality of hydrogen-fuelled and hydrogen/natural gas dual-fuelled or converted appliances including: boilers, cookers and fires.

5. Identification of the SoA: Safety in maritime FC applications

The following five steps are common for the approval of a seagoing ship as a simplified procedure according to IMO MSC.1/Circ.1455:

1. Development of a preliminary design.
2. Approval of the preliminary design (Approval in Principle).
3. Development of the final design.
4. Final design testing and analyses.
5. Approval.

5.1 Safety Assessment Methodologies

As in other sectors, the following methodologies for identifying and mitigating risks are common in the maritime sector:

FMEA (Failure Mode and Effects Analysis) is an analytical method of reliability engineering that provides qualitative statements. Possible product defects are evaluated according to their significance for the customer, their probability of occurrence and their probability of detection, each with a key figure. The FMEA lacks the severity, occurrence and detection classifications. Although there are FMEA templates that include these fields, strictly speaking, severity and criticality are assessed in the FMECA. This methodology is very common as well in automotive, aviation and space industries. The FMEA serves to increase technical reliability.

HAZID (Hazard Identification) is a structured method for identifying hazards, threats and consequences associated with a process, operation or area. It allows a high-level evaluation of risk at an early stage of a project, covering issues such as: facility siting, human factors, MAH (Major Accident Hazards) scenarios, environmental impact and best engineering practices.

HAZOP (Hazard and Operability) is a systematic investigation to identify and evaluate problems that may pose risks to personnel or equipment. The aim of a HAZOP study is to review the design to identify potential problems during the operation of a system. The technique is based on breaking down the complex overall design of the process into a series of simpler sections, which are then reviewed individually. It is carried out by a suitably experienced multidisciplinary team.

Typically, the HAZID study as a method for general hazard identification normally carried out prior to HAZOP that focuses more on process hazards. As an instrument of quality management, FMEA therefore usually is carried out before the product is produced - i.e. in the early development phase because preventive measures are most effective the earlier they are started.

5.2 Basic safety principles for handling Hydrogen

In order to be as safe as conventional technology, certain safety principles must be observed especially when using fuel cell and hydrogen based systems on board ships. Some important and basic safety principles and their practical application are described below.

The following safety principles for systems are generally valid and not specifically limited to maritime applications. Compliance with the rules set out is a common standard in the handling of hydrogen:

Tightness

Tightness is understood to mean the complete sealing of a pressurised space from its surroundings. Gas pipes, connecting elements and other gas-carrying components and systems must be tight up to a defined detection limit. In principle, there is no such thing as absolute tightness, just as there is no such thing as absolute safety, but no gas must escape and no explosive gas-air mixture must be able to form. This tightness must be guaranteed for all operating conditions for which a component or system has been designed.

Detection of leaks

Within the scope of a leak test, gas-carrying equipment, e.g., gas pipes, connecting elements, components or systems must be checked. This may also include hydrogen detection systems or pressure detection methods.

Avoidance of ignition sources

Hot surfaces, flames and hot gases can be potential ignition sources and must be avoided as far as possible in the immediate vicinity. The same applies to electrical currents, electrical potential differences, electrostatic charges, electromagnetic fields, ionising radiation, etc. Sparks generated mechanically (friction, impact and abrasion processes) or electrically (electrical equipment, safety, control and regulating devices) must be avoided at all costs.

Ventilation and warning

To prevent major accumulations of hydrogen indoors, exceeding a certain gas concentration should be prevented by safely shutting off the hydrogen supply through redundant quick-acting shut-off valves.

Sufficient ventilation is an important primary safety measure for hydrogen systems in enclosed spaces. The required ventilation volume results from investigations of possible incidents such as leaks, line breaks or diffuse leaks. At least for diffuse leaks or for quantities of gas trapped during plant shutdown, for example, ventilation sufficient for the expected release volumes should be provided. It may also be necessary to provide gas-tight pipe penetrations and doors or forced ventilation between potentially explosive atmospheres and other spaces. Ventilation equipment should prevent the formation of explosive or toxic atmospheres and their carry-over in the event of gas leaks. Supply air should be introduced near the floor and exhaust air should be drawn in at the highest point of the room.

Damage prevention / damage control

Between media of different flammability, constructive measures of preventive fire avoidance or fire consequence reduction can be taken (e.g. fire-resistant or fire-retardant walls and doors). Other preventive or mitigative measures include defined, structurally designed relief areas that provide pressure relief in the event of an explosion and thus ensure damage limitation to load-bearing parts, as well as signposted evacuation routes.

5.3 Safety principles at maritime applications and exemplary implementation

With regard to maritime applications, the following rules have become established, which are based on the measures described above, but go one step further:

Single failure criterion

In general, the single failure criterion is applied. This means that the fuel cell system should be designed in such a way that no single failure can lead to an incident. In addition, all safety-related components must be certified for their intended use [14].

The two-barrier principle of hydrogen lines

The two-barrier principle for H_2 supply means that each H_2 line is surrounded by two independent barriers. If one barrier fails, the other barrier ensures the safe containment of the released H_2. Several measures can be taken to comply with the two-barrier principle. The principle can be implemented either by double-walled ducts as shown in Figure 8, H_2 ducts in the ventilation duct, or H_2-tight enclosures (e.g. gas-tight storage room, gas-tight fuel cell enclosure, etc.).

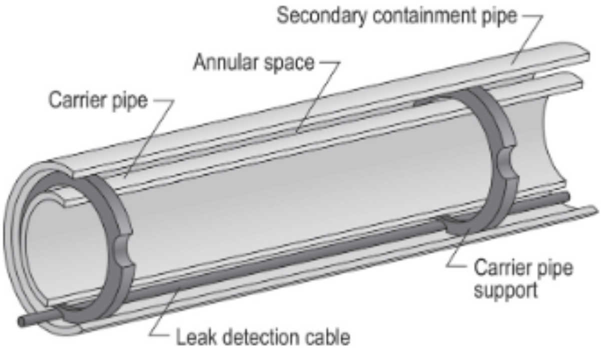

Figure 8: schematic of the double-wall duct concept

A pressure sensor between inner and outer pipe can be used to monitor the barrier failure of a double-walled pipe. To do this, the pressure level between the pipes must be lower than the pressure in the inner pipe and higher than the ambient pressure. In this way, the failure of the inner and outer barrier can be detected. A failure of an H_2 pipe in the ventilation duct is usually detected by an H_2 sensor at the end of the ventilation duct.

Separation of systems

In general, safe areas should be separated by an H2 seal from areas where potentially hazardous atmospheres may be present. Following the two-barrier principle, H_2 systems can be separated by a e.g., double block ventilation configuration (Figure 9), spaces can be separated from the fire load by fire resistant insulation (e.g. A-60 insulation[6]) or airlocks and, for the ventilation air flow, by a separate, self-contained ventilation system for the space in question (H_2 storage space, fuel cell enclosure, etc.). The H_2 storage room and the fuel cell containment room should be separated from the other rooms such as battery compartment, electrical installations, machine

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[6] During the evaluation of the IGF code in scope of the e-SHyIPS project, a gap with fire insulation was detected. It cannot be verified at the moment, that the A-60 insulation protects in case of hydrogen fire. This should be considered.

rooms, etc.. In addition, the H_2 storage room must be separated from the fuel cell installation area.

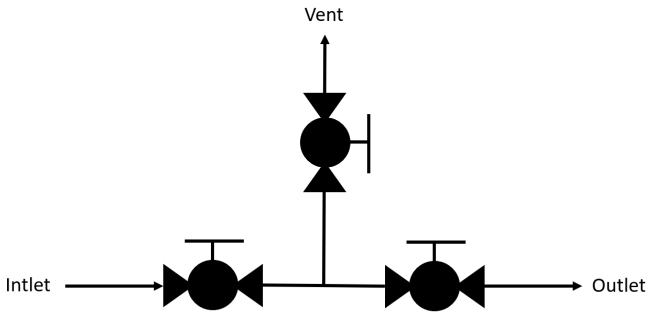

Figure 9: Example of a double block and bleed configuration

Safe gas ventilation

To ensure safe operation of the fuel cell system, various ventilation systems are installed. These include the venting of combustible gases through safety valves. When pressurised hydrogen (GH2) is used as fuel, as in the FCS ALSTERWASSER (ZEMSHIP project of partner PROTON MOTOR), where hydrogen is stored at 340 bar, fusible plugs can be used to depressurise the gas cylinders in case of fire. Ventilation during normal operation includes ventilation of spaces containing H_2 and fuel cell exhaust gases, which may also contain flammable gases. The ventilation ducts must be installed in such a way that these ventilation systems cannot create a hazard. To this end, the ventilation openings must be installed in such a way that there are no ignition sources in the vicinity, that a sufficient distance to the safe areas is ensured and that no dangerous gases or vapours can be drawn into the safe areas. In the case of high-pressure ventilation ducts for melting plugs and safety valves, it must also be ensured that the ventilation openings are installed vertically upwards.

Protection against explosion

To avoid the risk of explosion, all areas where H_2 may be present must be suitable for this purpose. Therefore, an area classification - generally in accordance with IEC 60079-10[38] - should be carried out to determine the hazardous areas and the required explosion protection measures. The classic explosion protection concept always consists of three phases (as also described before):

(i) avoidance of explosive atmospheres - for example this can be realised via ventilation, two-barrier principle, prevention of H_2 accumulation, permanent sealing systems [e.g., welded pipes]).

(ii) avoid ignition sources - for example this can be realised via use of certified equipment only, temperature below 80% of auto-ignition temperature, avoid electrostatic charges).

(iii) Reduce the effects of explosions - for example this can be realised via separation of compartments, double block and sockets, double barrier principle, active and passive fire protection measures, use of non-combustible materials).

Protection of high-pressure vessels

One of the most critical potential failures is the rupture of a pressure vessel due to overpressure, fire, etc. The rupture of a pressure vessel must therefore be avoided at all costs. Therefore, the pressure vessel must be protected by active systems, such as combined fire detection and extinguishing systems, and passive systems, such as fusible plugs and safety valves. It should be mentioned that "real" safety valves must be installed, not just uncertified flow relief valves. In general, it should be noted that all pipes designed for lower pressure must be protected against overpressure with suitable measures.

Protection against external influences

In order to avoid malfunctions of the fuel cell system on board, it should be designed for the typical environmental conditions on board. In addition, the fuel cell system must be protected against external influences such as impact, mechanical damage and fire. Fire is the most critical failure, especially in maritime transport. To avoid problems caused by external influences, the following measures are generally used. To avoid collision damage, the location of the fuel cell should be chosen accordingly (e.g., at a sufficient distance from the hull). Mechanical damage can be avoided by appropriate shielding. For example, this can be realised via protective plates on the H_2 pipes. Fire risks can be minimised by appropriate passive and active fire protection measures commonly used in maritime transport. For example, this can be realised via fire protection insulation, fire extinguishing system.

Safety control

In general, all components of the safety chain should be certified for their intended use. For critical systems, SIL (Safety Integrity Level) certification or equivalent redundancy is required. The main safety-related monitoring systems are the fire and H2 detection systems in the H_2 storage and fuel cell installation room. In general, the alarm and shutdown limits of the H_2 detection system should be 10% and 40% of the lower explosive level (LEL) respectively. However, this should be considered in detail, taking into account the location of the sensors and their response time. If ventilation is integrated into a safety system or explosion protection concept, airflow monitoring is necessary. If the ventilation is not functioning, the system must be shut down to avoid undefined dangers. Depending on the specific design of the installation, other control systems may also be necessary. For example this can be realised via level switches for water separators in the water treatment line, etc..

Other issues to consider

In addition to the technical design of the system, it is very important to look at the operational procedures. Therefore, the manual should contain a detailed description of operating instructions for refuelling, starting and stopping the system and emergency extinguishing. During the commissioning phase, it is important to check that the system is functioning properly. This includes, for example, pressure and leakage tests, functional tests of the fuel cell and its integration, as well as tests of the safety system and the safety chain. After commissioning, regular checks of the various system components are necessary to ensure the safety of the system This may be conducted with calibration of the hydrogen sensors, regular inspection of the storage tanks, regular leak test, functional test of the safety chain, etc. for example.

The following **Errore. L'origine riferimento non è stata trovata.** shows a summary of these described safety principles:

Basic principle	**Description or example**
Single failure criterion	Fuel cell system design that no single failure can lead to any dangerous situation
Two-barrier-principle for gas supply	e.g., second barrier, double-wall-piping etc.
Separation of systems	Separation of rooms / installation spaces of batteries, gas storage, fc enclosure etc.
Safe venting of gases	e.g., venting lines on top (so that no hazard can occur) etc.

Avoiding risks resulting from flammable and explosive Gases	a) prevention of explosive atmosphere, b) prevention of ignition sources minimising of fire loads, c). reduce effects of explosion
Protection of high-pressure storage vessel	e.g., overpressure relief valves etc.
Protection from external Influences	e.g., against external influences like collisions, mechanical damage and fire.
Safety monitoring	e.g., hydrogen gas detectors, alarms at certain levels and induced appropriate measures as defined
Further things to consider…	e.g., organisational things, like maintenance plan, documentation etc.

Table 5: Short overview on basic safety principles onboard of vessels

The following illustration (Figure 10) shows the basic safety concept of the FCS Alsterwasser passenger ship as a very early maritime application of Proton Motor (2010). This ship was approved by the classification society Germanischer Lloyd (GL), which has been merged into project partner DNV (formerly DNV-GL). It can be clearly seen that all described safety measures have been applied and it may be interpreted as an early proof-of-concept as this ship has expired an emergency situation [39] without any personal injury.

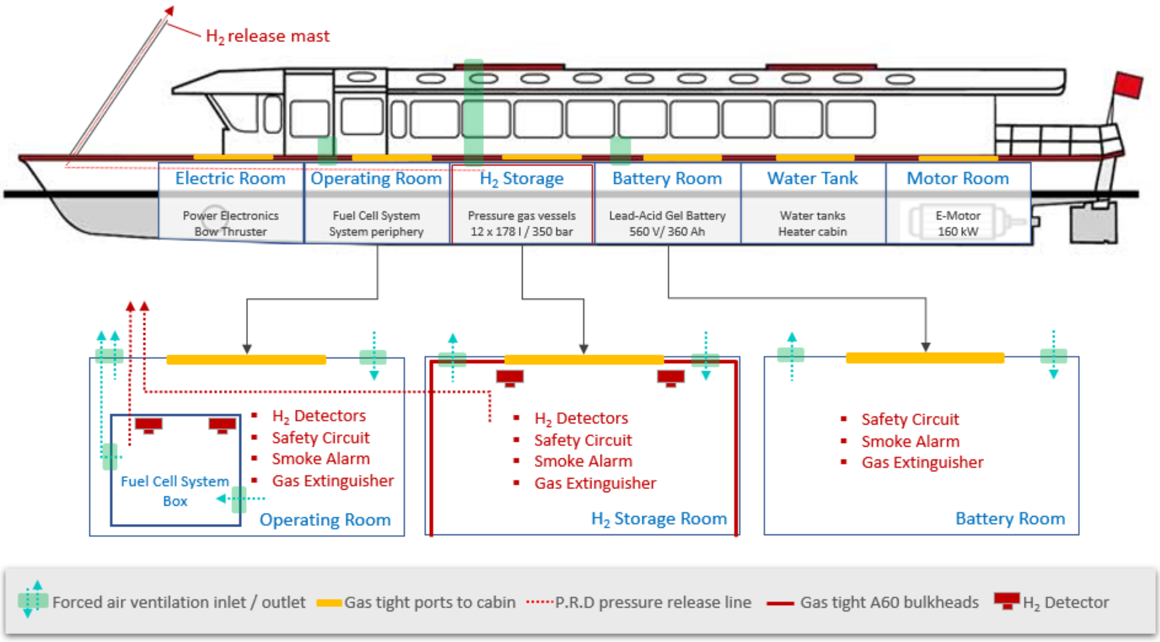

Figure 10: Safety concept of the FCS Alsterwasser

5.4 Identification of gaps

The following gaps have been identified so far:

(i) Lack of specific Hydrogen requirements
(ii) Lack of Prescriptive Hydrogen requirements

During the ongoing WP1 development of the e-SHyIPS Project, regarding the methodology to run this review of the IGF code to identify potential "gaps", two parallel routes are being put in place:

Following the current structure and sections of the current IGF Code, Spotting similarities between natural gas and hydrogen, so requirements missing in the IGF code that may be parallel to the one related to natural gas can be identified.

Focusing on the Hydrogen Properties and Hydrogen technology particulars, to identify missing sections that should be included. (For instance, Fuel cells are not included into the powering systems considered in the current IGF Code and it is the preferred technology in the three scenarios adopted in e-SHyIPS).

6. Conclusion

This deliverable summarised the framework and state of the art regarding available hydrogen-based fuels and alternative fuels and their application on passenger ships, fuel cell technologies and capabilities.

First, the general framework conditions that apply were compiled for this purpose.

The different fuels and energy carriers that can generally be used for ships were compared and the special position of hydrogen (LH2 and GH2) was elaborated. The project consortium decided to focus exclusively on hydrogen itself and not on hydrogen carriers (biofuels, methanol, ammonia LOHC etc.). This is initially also purposeful since both; the energy yield and the technical implementation are most advanced here.

Furthermore, the focus was on passenger ships. This means that cargo ships, tankers and tugboats are explicitly excluded. Nevertheless, the findings from this project as described in this deliverable can be modified and adapted to the respective application.

Based on these prerequisites, the specifics for hydrogen in general were presented, which partly differ depending on the storage type.

The specifics of fuel cells are the subject of the following chapter, focusing on SOFC and PEMFC, as these fuel cell types have by far the greatest potential and the highest technical maturity. In general, however, the statements made also apply to other useful types.

In order to identify the technical knowledge gaps and models for risk assessment and risk management of gaseous and liquid hydrogen (GH2 and LH2) on ships, the methodologies currently used were first identified and explained. Furthermore, the strategies for the prevention of hazards resulting from the use of fuel cells and hydrogen on board ships are specified. These are essentially aimed at avoiding unintentional H_2 release or discharge into safe areas (Ex zones).

With the recently published INTERIM GUIDELINES FOR THE SAFETY OF SHIPS USING FUEL CELL POWER INSTALLATIONS by the IMO (June 2022), a significant step has already been taken in the right direction. Nevertheless, detailed questions are not yet 100% clarified and will be dealt with in the framework of the e-SHyIPS project in this and other work packages.

Regarding relevant Publicly Available Standards, it was found that no direct and only few relevant PAS in the wider field of hydrogen and fuel cells especially in respect of maritime applications are available right now and novel developments are currently not known.

In particular, due to the fast and uncomplicated implementation of a PAS compared to normal national and especially international standards, a lot of valuable potential may be wasted here. This at least is the view of the authors.

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