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English version

Pre-normative plan for H2 applications to passenger ships - Recommendations for H2 passenger ships from the early stage of design

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European foreword

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Introduction

This CEN Workshop Agreement is based on the results of the e-SHyIPS European project (Ecosystemic knowledge in Standards for Hydrogen Implementation on Passenger Ship) grant agreement No 101007226.

The maritime sector contributes significantly to the environmental impact, with an increased share of greenhouse gas emissions estimated for the next few years. The IMO (International Maritime Organization) has initially set a target to reduce CO_2 emissions by at least 50% in 2050. Recently, this strategy has been revised by IMO aiming for an ambitious zero-emissions scenario by the same year, towards the complete decarbonization of the maritime sector. In this context, hydrogen and hydrogen-based fuels are regarded as very promising, and a broad consensus has been reached within the shipping industry to replace conventional propulsion systems of vessels with new hydrogen technologies in the near future. Achieving the target, also requires an unprecedent enhancement in innovation for the maritime sector, involving not only the re-design of vessels, but also the implementation of new infrastructures in ports as well as the development of alternative bunkering approaches, to support the whole value chain related to hydrogen as fuel. Fuel cells and hydrogen technologies have been already demonstrated in few prototypes, at different scales and for different applications. However, to date, an international regulatory framework for the use of hydrogen on-board of ships is absent, this representing a barrier to its adoption at large scale.

In 2021, the IMO has released the Interim Guidelines for Fuel Cells, as a first step towards the development of prescriptive rules for hydrogen systems on-board of ships. Since then, significant progress on the development of guidelines for the safety of ships using hydrogen as fuel have been made, and on 20-29 September 2023 the Sub-Committee on Carriage of Cargoes and Containers (CCC 9) of IMO agreed to finalize and bring the approval of the draft interim guidelines to December 2024. These guidelines will represent a first try-out for the market to underpin the future IGF Code (International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels) update, which, to date, covers LNG (Liquified Natural Gas) as a fuel, while it does not consider either liquid LH2 (Liquid Hydrogen) or CGH2 (Compressed gaseous hydrogen). According to the IMO agenda, amendments to the IGF Code will be ready to entry in force not before 2028. In this framework, the urgent need of providing crucial insights related to the use of hydrogen technologies for maritime applications emerges clearly, to speed up the process of improvement of the existing standards.

1 Scope

This document provides a set of design and installation recommendations for the arrangement and installation of propulsion systems, using hydrogen as fuel, on passenger ships. No new safety requirements are defined in the CWA, but these recommendations can be used for a risk assessment, leveraging on existing standards and practices (e.g. HAZOP, HAZID, FMECA), to be applicable already from the early design phases and discriminating based on the presence of passengers on board. While the recommendations covered in this CWA can be useful during a risk assessment (to be caried out in a second stage), they are not the focus of this work. The document leverages on the results of the experiments carried out within the EU e-SHyIPS project. Ultimately the document is expected to benefit the industry also in terms of knowledge sharing and policy makers for the update of relevant documents.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

No terms and definitions are listed in this document.

4 e-SHyIPS approach

4.1 e-SHyIPS project

The e-SHyIPS project aims to contribute to the development of new guidelines for the effective deployment of hydrogen in the 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 navigation scenario.

By means of an ecosystem approach, e-SHyIPS proposes theoretical pre-normative research activities on standards, simulation and laboratory experiments, involving stakeholders from maritime, technological, and hydrogen sectors.

The ecosystemic framework developed within the project, called e-SHyIPS Learning Ecosystem, aims to create formalized and shareable knowledge within its specific research context. The stakeholders of the ecosystem interact with each other and external sources to populate a dynamic system, generating, managing, and exploiting comprehensive knowledge.

The e-SHyIPS project is structured based on five pillars each one representing a line of research and experimental activities:

- Pillar 1 - State of the art and theoretical studies;
- Pillar 2 - Ship design experiments;
- Pillar 3 - Safety system experiments;
- Pillar 4 - Material and components experiments;
- Pillar 5 - Port – bunkering – ship interface experiments.

In the early phase of the project three scenarios of vessels have been defined, i.e. Scenario S, Scenario M, and Scenario L. These scenarios differ from each other by size of the vessels and especially, operational profile and were shaped by data collected during contextual inquiry activities and subsequently validated through structured and semi-structured interviews with a focus group. This group included industry experts engaged in vessel design, development, maintenance, operation, and the creation of hydrogen fuel solutions. Despite the project and its developed methodology being vessel-independent, with differentiation based on the type of hydrogen (liquid or gaseous) rather than the type of vessel, the scenarios play a crucial role in contextualizing the research activities being undertaken.

4.2 e-SHyIPS Learning Ecosystem

The e-SHyIPS Learning Ecosystem (see Figure 1) is a methodological framework to create a systemic database of knowledge. It works to create formalized and shareable knowledge within the specific e-SHyIPS research context, with the aim to advance knowledge on the introduction of pre-normative standard on hydrogen fuel-based applications in passenger ships.

Defined by a set “of stakeholders incorporating learning processes and learning utilities within specific environmental borders” [1], the e-SHyIPS Learning Ecosystem is constituted of five core elements: the Learning Boundaries, the Stakeholders, the Learning Contents, the Learning Process, and the Learning Flow.

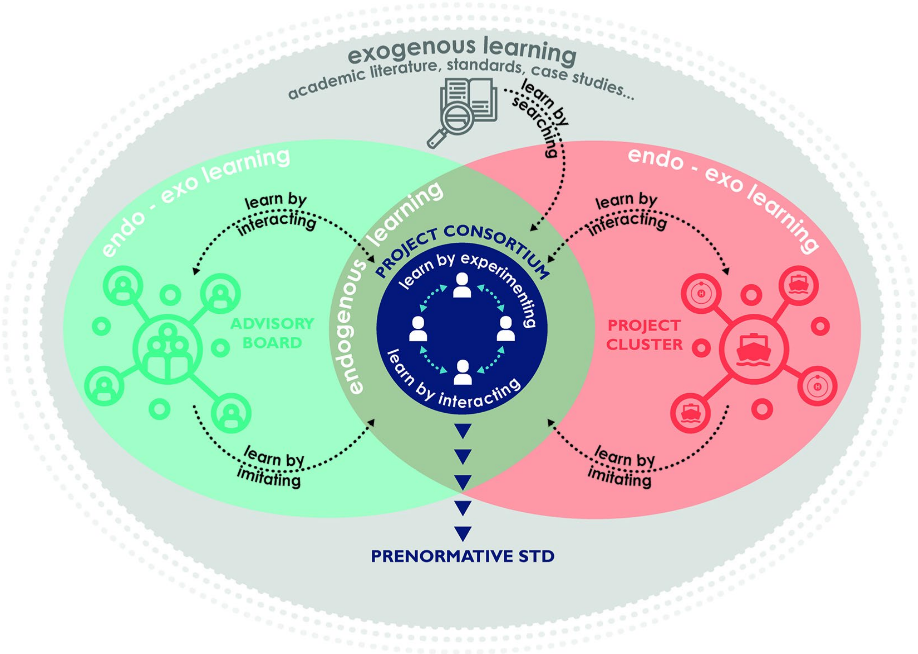

Figure 1 – e-SHyIPS Learning Ecosystem (e-LE)

The **Learning Boundaries** define the physical and logical borders of the learning system, determining whether the components and their attributes associated to the ecosystem are internal or external to the reference project. There are three different portions of the ecosystem, as defined by the mentioned boundaries:

- Endogenous Learning, everything that happens exclusively inside the Project Consortium, within project’s members, representing the closest environment to the project itself;
- Exogenous Learning, everything that happens exclusively outside the Project Consortium and put the e-SHyIPS project in relation with knowledge that is externally generated and independent from the project itself;
- Endogenous/Exogenous Learning (shortened in Endo-Exo Learning), everything that is not properly Endogenous nor Exogenous, and that simultaneously involves both dimensions. Two main environments have been structured with these characteristics: an Advisory Board made of experts

in the fields of hydrogen and maritime technologies, and a collection of projects, funded around similar e-SHyIPS topics.

The e-LE **Stakeholders** are a group of actors involved in the ecosystem who share common objectives and attitudes and interact and collaborate synchronously or asynchronously. Specifically, the e-LE stakeholders are the 14 members of the project consortium, which assumes different and complementary roles in the e-LE. The e-SHyIPS partners can be grouped according to their expertise, consequently emphasizing in which aspect of research they can give the greatest contribution to. They are distributed across four expertise clusters, namely:

- Basic research centers and H2 (Hydrogen) associations;
- Maritime sector;
- FCH and H2 industrial mature sector;
- Terrestrial transport sector.

The **Learning Contents** can be defined as the topics, themes, beliefs, behaviours, concepts and facts that are often grouped into knowledge, skills, values, and attitudes expected to be learned. Within the e-SHyIPS project four areas have been identified as main knowledge domain to be investigated as objects of endogenous and exogenous learning processes. The four areas, each corresponding to one work package, are Ship design (WP2), Safety systems (WP3), Material and components (WP4), Port – Bunkering – Ship solutions (WP5). Additionally, a building block with the State of the art and theoretical studies represents the basis the overall research activities are built on (WP1), with the final aim at developing useful knowledge, able to contribute to pre-standards and road mapping activity for H2 inclusion in maritime.

The **Learning Process** consists of the activities carried out by the learning stakeholders in order to acquire new knowledge, skills, values, or attitudes that will eventually influence their decisions and actions. The different stakeholders can interact, internally or externally, through a list of learning mechanism:

- Learn by searching, acquire existing useful knowledge by searching it among academic literature, case studies and standards. This kind of learning refers to an exogenous learning, since the source of searched knowledge is external to the project consortium.
- Learn by imitating, learning from the passive or active observation of internal or external entities. Since this learning happens either within internal or external subjects, it’s considered a kind of learning that takes place under an endo-exo learning environment.
- Learn by interacting, learning from the interactions among internal and/or external stakeholders. Similar to the learn by imitating, this learning occurs within both internal and external subjects, and it’s hence happening within an endo-exo learning environment.
- Learn by experimenting, learning from attempts of utilization and R&D activities. This kind of learning is entirely taking place within the project consortium and can be considered within the endogenous learning boundary.

The **Knowledge Flow** (see Figure 2) can be delineated within the context of e-SHyIPS through three main phases:

- Knowledge gap identification: A knowledge gap is defined as a lack in expertise, skills, or know-how, arising from a misalignment between required and existing knowledge among stakeholders [2]. This gap is identified through three phases: defining knowledge needs, assessing available knowledge, and pinpointing the gap itself, facilitating effective gap closure strategies. This phase motivated a dedicated focus on the IGF Code, aiming to recognize gaps pertinent to its application in hydrogen-powered vessels. This stage was meticulously addressed through a series of workshops involving project partners and the Advisory Board.

- Knowledge gap resolution: this is the systematic process of addressing disparities in understanding, or in the expertise among individuals, teams, or organizations, with the goal of fostering enhanced comprehension. In this phase, the Learning Process comes into play, describing the various strategies by which actors within the e-LE can acquire knowledge to bridge the identified gaps. Nevertheless, knowledge is derived from the act of learning, which necessitates the establishment of a learning process, as well as an examination of the evolving dynamics within it, in order to both gain and generate knowledge.

- Knowledge capitalization: After knowledge has been acquired, it should be either transmitted or shared, and ultimately applied within the project's context. This phase represents the ultimate objective of the system and is where the e-LE can truly deliver significant added value. It's not enough to merely generate knowledge; it is crucial that this knowledge is leveraged and made accessible both internally and externally [4] [5]. In this phase, the project's outcomes are emphasized through a strategic focus on communication, dissemination, and the exploitation of knowledge.

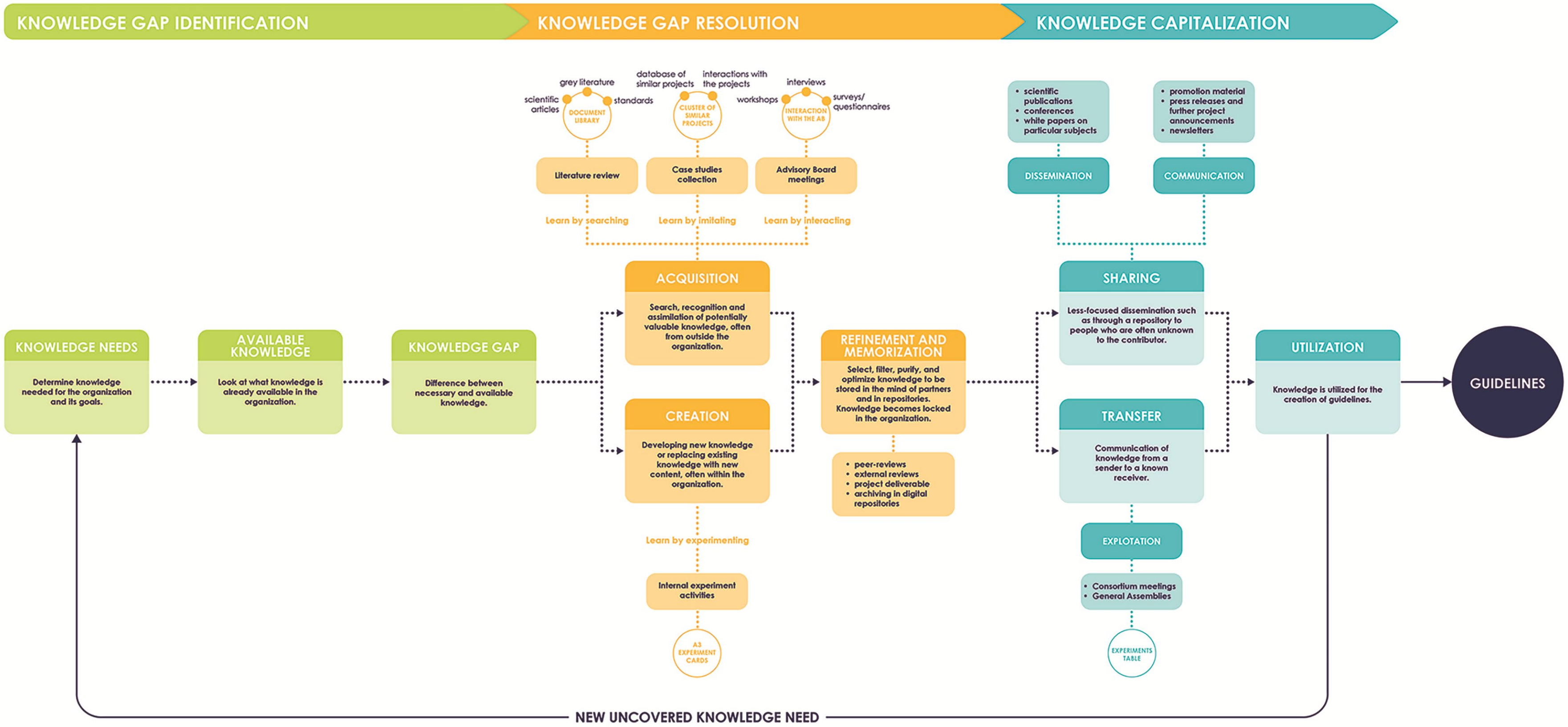

Figure 2 – e-LE Knowledge Flow through knowledge gap identification, knowledge gap resolution, knowledge capitalization

5 Methodology guidelines for design H2 passenger vessel

5.1 General

In the design of both conventional and zero-emission ferry vessels, safety considerations for both passengers and crew should be always integrated. As vessel design and engineering are highly interconnected, safety aspects form a fundamental part of the e-SHyIPS research, and, therefore, the methodology guidelines and the set of recommendations provided in this section take necessarily safety aspects into account. These recommendations are built in a framework of design for hazard minimization. However, no new safety requirements and safety matters are introduced in line with the scope of this CWA.

Within the e-SHyIPS project the consortium has developed a comprehensive methodological approach to facilitate the effective deployment of hydrogen in the maritime passenger transport sector. This approach aims to boost zero-emission navigation within the global and EU strategies for a clean and sustainable environment. The adoption and implementation of hydrogen technologies in waterborne transportation represents a challenge involving complex activities that include not only the design of new vessels, but also the definition of suitable waterborne bunkering strategy. For this reason, designing a hydrogen-fuelled vessels requires constant interaction within stakeholders: shipyard, transport operator, hydrogen provider, fuel cell technology provider, research centers/expert in risk assessment, port authorities, classification bodies, flag representative, and standardization bodies.

The e-SHyIPS Methodology has been developed to guide professionals by introducing a set of holistic guidelines that enable and support the design of H2 passenger vessels from the operational requirement definition phase to the General Arrangement design phase for preliminary design approval (IMO Approval process of alternative design and arrangements[1]). The developed methodology applies to the first three steps of the implementation of a hydrogen system onboard a vessel[2] – feasibility studies, specification outline, and Design and procurement – and should be seen as a self-assessment process. The Methodology Guidelines should be used in conjunction with the IMO and SOLAS (Safety of Life at Sea) regulation, as well as other appropriate engineering design guides, it is not intended to serve as a stand-alone document and is in no means prescriptive.

The overall methodology is represented though a flow diagram (see Figure 3) and encompasses three main steps:

- Step 1: from operational requirements to technical requirements definition;
- Step 2: from technical requirements to technical specifications definition;
- Step 3: technical specifications to General Arrangement (GA) design for approval process.

These steps of the methodology are further detailed in the next clauses with considerations for General Arrangement design, Material and component selection, and bunkering strategy definition.

[1] IMO (2019) MSC.1/Circular.1212/Rev.1 - Revised Guidelines on Alternative Design and Arrangements for SOLAS Chapters II-1 and III

[2] Reference to DNV, G. (2017), Study on the use of fuel cells in shipping. European Maritime Safety Agency (EMSA)

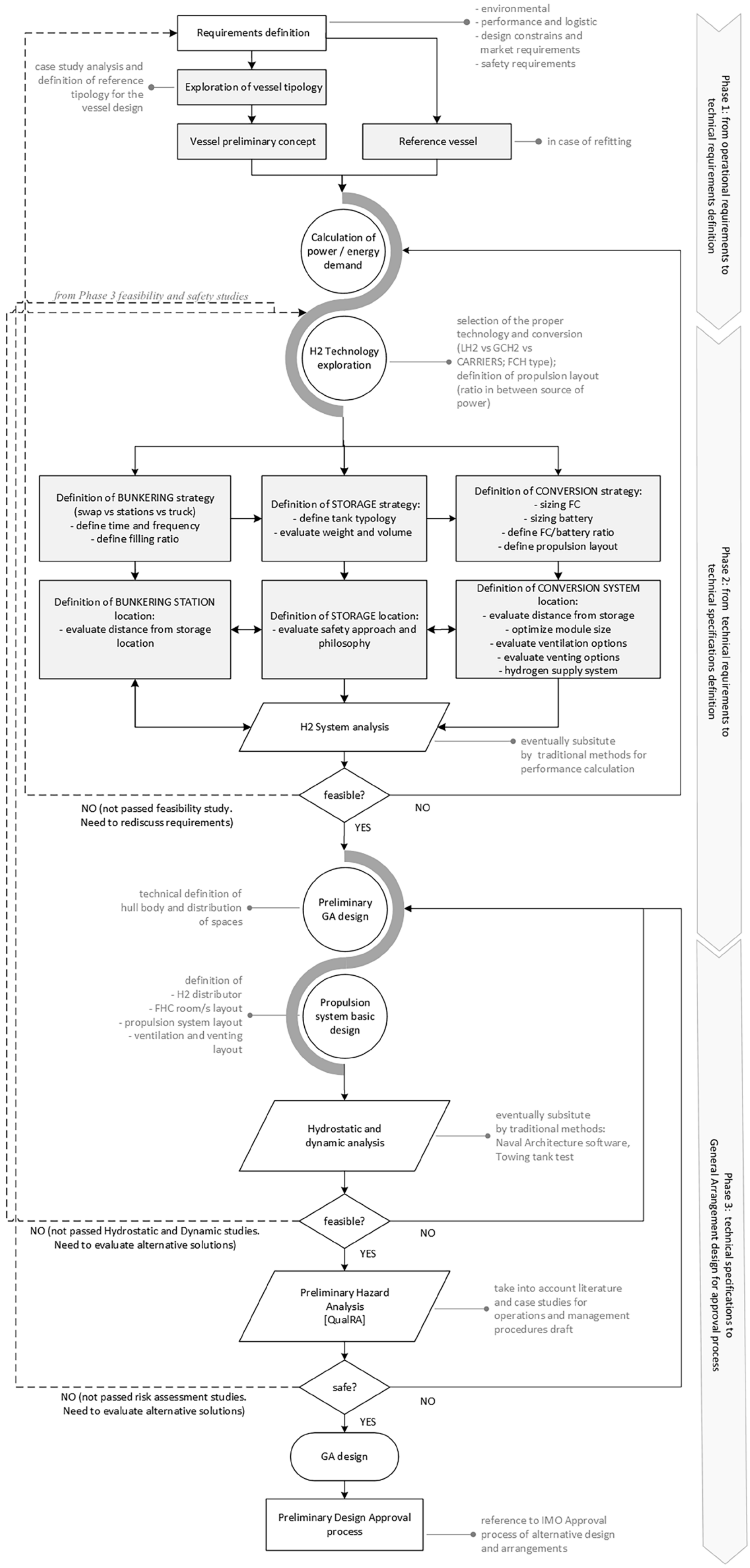

Figure 3 – Flow diagram of the methodology approach for design H2 passenger vessel

Step 1 involves defining the operational requirements, which qualitatively describe the system functions or tasks to be performed in operations, essentially outlining the basic vessel behaviours to meet user and market demands. This includes the formulation of:

- Environmental requirements: e.g. type of voyage (inshore, offshore, coastal…), wind speed, significant waves height and periods, depth of waters;
- Performance and logistic requirements: e.g. human factors, ergonomics, availability, maintainability, and reliability, cruise speed, range, number of round trips to be performed, fuel autonomy, energy demand;
- Design constraints and market requirements: e.g. no. of passengers/ crew members, vehicles, freight;
- Safety requirements: according to the IMO IGF code the vessel shall be as safe as conventionally powered vessels and the reliability of the complete system should be at least as good as a conventional vessel.

The design process of H2-fuelled passenger vessels generally follows conventional practice for maritime applications where the stakeholder expectations are translated into a definition of the problem and then into a complete set of validated technical requirements through case studies analysis and exploration of different vessel typology options. Reference vessel could be adopted in case of refitting or re-engineering of previous ferry models.

In step 1, the principal stakeholders involved include ship owners and ferry operators, shipbuilders, ship designers, and port authorities.

Step 1 is in connection with step 2 through a loop of investigation for the calculation of power/energy demand and selection of proper technology for H2 storage and energy conversion.

Step 2 aims at performing a feasibility study before making the final decision regarding the possible design of a hydrogen-fuelled vessel. It starts from the definition of technical requirements by identifying factors that should be met for the vessel to respond to users/market needs (operational requirements). These describe how the system's needs should be fulfilled. Technical requirements specify the parameters that should be present in the system to resolve technical challenges. During this stage, it is essential to consider the expected operational modes and profiles, load variations, the targeted system lifespan, and possible bunkering strategy.

Technical requirements serve as the foundational guidelines that drive the following design stage. For this reason, it is essential to perform a feasibility study on the selected H2 technology before moving to the General Arrangement preliminary design. It is suggested to perform an evaluation on bunkering, storage strategy, and conversion strategy in parallel, defining at first the size (volume and weight needs) and then the possible locations of components onboard. In this step, applicable standards and regulations should be considered, including the applicability of the Alternative Design. Furthermore, the safety and reliability of the hydrogen systems should be prioritized.

In step 2, the main stakeholders involved are ferry operators, shipbuilders, ship designers, technology providers, and H2 providers.

The dimensioning of the hydrogen systems is influenced by the vessel power demand, the degree of hybridization, and the characteristics of available bunkering infrastructure.

In case of negative results of feasibility studies, a new evaluation of H2 systems shall be considered, and the process iterated, along with a re-definition of the operational profile if necessary.

The result of step 2 is the definition of one or more preliminary General Arrangement and H2 propulsion system, through a loop of design refinements. While technical requirements are the input to step 2, technical specifications are the output.

Step 3 is a direct outcome from the technical specifications that include the evaluations of vessel stability, performance, and risk assessment that is prior to the IMO Alternative Design and Arrangements approval process. However, it is recommended to initiate the Alternative Design and Arrangements approval process and the related contact with the Administration during this stage, to discuss the initial approach to the vessel design.

In step 3, the principal stakeholders include are ferry operators, shipbuilders, ship designers, technology providers, certification and flag bodies.

H2 systems shall demonstrate robustness for exposure in a marine environment and sailing conditions, including trim, roll, and acceleration due to wave effect. Stability simulations should be used to verify that the preliminary arrangement and main compartment definition are acceptable in terms of ship stability. This methodological step aims to verify that the reliability of the entire vessel is equivalent to that achieved with conventional fuel systems. It is suggested to use “calm waters” simulation to compute preliminary power resistance curve in order to verify the feasibility of the identified propulsion system. Wave hull interaction simulations, for both zero hull velocity (bunkering), and non-zero hull velocity (cruise speed seakeeping), are, therefore, essential to verify both resistance in waves structural stresses of the tanks, supports, and FC system. Results from wave hull interaction simulations should be discussed with H2 technology suppliers to select the proper tanks and machineries equipment.

In case of positive response on hydrostatic and hydrodynamic studies, a preliminary QualRA (Qualitative Risk Analysis) shall be carried out.

Risk assessment has a vital role in this step since passenger and ship safety, as well as reliability of systems are affected by every decision taken during the early design phases – when technical specifications are translated into shape and location of compartments. A risk assessment analysis that can be performed with less mature data has critical importance. Furthermore, QualRA should consider operations and management procedures that may play an important role in the overall level of safety.

The proposed methodological approach suggests HAZID (Hazard identification) as a tool to identify hazards, their associated causal factors, effects, level of risk, and mitigating design measures when detailed information is not available. Furthermore, FMECA (Failure Modes Effects and Critical Analysis), according to EN IEC 60812, could be introduced as a systematic analysis of the H2 systems to identify potential failure modes, their causes, and their effects on performance. Risk assessment is essential to gain critical knowledge for the development of passenger ship concepts – especially in the translation of functional and safety requirement specifications into a general arrangement design. The QualRA shall be performed including all the relevant stakeholders for ship design, construction, operation, and certification. HAZID and FMECA analysis serve as a guide to rank and prioritize the focus of quantitative simulations to be performed at the vessel and system level in the Alternative Design and Arrangements approval process.

In step 3 one or more preliminary vessel design should be evaluated, taking into consideration the importance of human factors, operations and management. An iterative investigation could include a re-evaluation of H2 alternative technologies or different operational profile.

The result of step 3 is the conceptual Vessel Design, including GA (vessel plan and sections), indication of construction material, information on equipment and drawings, characteristics of operating and sailing condition for the vessel, preliminary quantitative hydrostatic and hydrodynamic analysis, qualitative analysis of hazards and risks.

5.2 Considerations for General Arrangement design

5.2.1 General

The General Arrangement (GA) design of a ship is a critical stage that outlines the spatial organization and layout of functional areas onboard. The GA serves as a comprehensive plan that reflects the overall distribution of spaces, providing both a top-down and side-view representation of the vessel, giving stakeholders a clear understanding of the ship's internal and external arrangements.

In passenger vessel design, the internal and external layouts of passenger, vehicle, crew, and machinery spaces are outlined. Key priorities in the GA design of passenger vessels include arranging machinery to meet operational requirements, efficiently managing passenger and crew flows, maximizing passenger comfort and onboard amenities, and ensuring system access for maintenance and emergencies.

The introduction of hydrogen-fuelled propulsion systems in GA design brings technical, operational and regulatory implications. These implications arise from the physical and chemical properties of hydrogen as a fuel and the infrastructure required for its storage, distribution, and use. The aim of this paragraph is to offer general considerations for the design and spatial arrangement of hydrogen (H2) storage systems and fuel cell (FC) power generation systems.

The design of hydrogen storage systems for passenger vessels necessitates strategic considerations to ensure operational efficiency.

5.2.2 General considerations on H2 system design

- For both fuel cell-powered vessels and battery/fuel cell hybrid-powered vessels, redundancy of the fuel-containment systems and energy converters should be considered.

- The positions of hydrogen components and rooms (e.g., FC spaces or tank hold spaces) should be chosen so that they are not in the vicinity of passengers, but are still accessible for maintenance, while offering as much protection from external hazards such as adverse weather conditions, impacts or collision etc.

- Distance & arrangement of H2 components (e.g. between bunkering station and tanks, or between tanks and FC rooms) should be controlled to reduce piping length/complexity.

- All H2 system spaces should be provided with safety system (e.g. H2 detection, ventilation, fire prevention). Natural ventilation can also be employed by arranging equipment on open deck, depending on the specific vessel typology.

- Single failure of critical modules should not compromise the integrity of the vessel or cause unacceptable power loss (i.e. prolonged, unrecoverable power loss). All safety systems should remain fully operational even in the event of a power failure (e.g. emergency discharge).

5.2.3 Considerations on H2 storage system design and location

- The choice for the hydrogen tanks needs to take into account: type, TRL (Technology Readiness Level), size, refilling time, material, cost, availability, lifetime, bunkering infrastructure availability and available weight/volume on board. Furthermore, tank producers shall demonstrate the component robustness for long-term exposure in a marine environment.

- The most suitable H2 storage capacity should be identified based on:

  i) the analysis of real vessel operating profiles, that are instrumental to retrieve the energy demand for both propulsion and auxiliaries,

  ii) the required bunkering frequency. The size of the hydrogen storage system should be calculated by taking into account any applicable margins for the design (e.g. harsh weather conditions), and always considering that the actually usable H2 in the tank is lower than the total stored amount.

  Realistic conversion efficiencies should be used (input from suppliers) and, for the FC, calculations should take into account the efficiency degradation at end-of-life condition.

- The reliability of the hydrogen storage system should be at least equal to that for conventional fuels.
- To ensure redundancy, at least two completely independent fuel-containment systems should be considered. Single failure of a critical module should not compromise the integrity of the system.
- Hydrogen storage areas should be isolated from passenger areas and other critical spaces. Access and openings to these areas should be arranged in a way that H2 cannot escape to spaces that are not designed for the presence of such gas (e.g. passenger compartment).
- Hydrogen storage areas should be protected against external hazards such as adverse weather conditions, human interference, fires, and mechanical impact.
- Hydrogen storage tanks should be located in a storage area where hazard caused by collision or grounding is minimized.
- Hydrogen storage tanks should be located in an area which is accessible for maintenance operations. Hydrogen storage tanks and fuel containment system should be located in areas which allow an immediate and a direct release of hydrogen in open air under undesired circumstances. Hydrogen storage tanks system should include emergency discharge systems, and all of that devices which are commonly used in hydrogen tanks commonly employed in other applications, and which are already regulated by international standards.
- Hydrogen storage tanks should be located in a fire-protected area.
- Hydrogen storage tanks and fuel containment system should be located in areas such that a fire will not (i) damage equipment in other compartments other than H2 system, (ii) damage the structural integrity of the vessel that may cause flooding of water below the main deck or any progressive flooding
- Due to their considerable high weight, H2 tanks should be located close to the vessel centreline and equally distributed in respect to the hull center of buoyancy.
- Open deck, if feasible, is an advantageous location for the H2 storage.
- In case of below-deck H2 storage location, the minimum safety distances to hull side and bottom should never be less than the one provided by the deterministic approach reported in IGF Code, 5.3.3. In case of lower deck installations, hydrogen storage compartments should be equipped with sufficient ventilation systems to prevent the accumulation of hydrogen gas.
- LH2 (Liquified Hydrogen) fuel containment areas should be studied to prevent the pooling of hydrogen and to ensure the structural integrity of materials in case of leaks.
- Boil-off effects and thermal management should be taken into account in the case of LH2.
- Distance between hydrogen storage areas and bunkering stations should be minimized to reduce losses, to reduce risks associated to the refuelling operations, and to avoid complex piping layouts.

5.2.4 Considerations on FC system design and location

- The feasibility analysis for replacing a conventional powertrain system with a hydrogen FC-based one needs to be assessed against real vessel duty cycles and by considering the size of components, weight and space requirements, their dynamic behaviour, and the level of hybridization with batteries.

- The choice for the hydrogen FC stacks needs to take into account power density as well as degradation aspects.

- As a general design approach, in a hybrid fuel cell/battery powertrain, the fuel cell should be able to provide at least the requested mean power, in order to avoid the battery state of charge depletion under continuous vessel operation. Therefore, in case of passenger vessels characterized by clearly distinguishable route profiles (e.g. different routing or round trips with upstream/downstream routing) the minimum requirement for the fuel cell sizing should be the mean power requested during the most demanding route. In any case, the sizing of the fuel cell should be made by ensuring that the required maximum power during real world operation can be delivered at end-of-life condition of the fuel cell.

- A suitable energy management strategy should be defined by considering that the powertrain should fulfil the vessel power demand during the whole mission. In particular, the fuel cell power output will depend on the degree of powertrain hybridization. A properly sized battery pack can help to improve powertrain efficiency, allow components downsizing, reduce costs and extend lifetime of components.

- The FC module layout should be designed taking into account redundancy and maintenance needs. Furthermore, FC room spaces should be accessible for replacement of parts of the system.

- Two completely independent energy converting systems should be considered, located in at least two different compartments. In particular, the battery system should be located in a different area from FC room.

- FC spaces design shall follow the "Interim guidelines for the safety of ships using fuel cell power installations"[3].

- FC spaces should be equipped with an effective mechanical ventilation system to maintain under pressure conditions in the room. Specifics CFD (Computational Fluid Dynamics) analysis to study the ventilation paths are recommended.

- FC spaces should be isolated from passenger areas and other critical spaces to minimize the risks to passengers and crew in case of leaks. Access and openings to these areas should be arranged in a way that H2 cannot be released to spaces that are not designed for the presence of such gas (e.g. passenger compartment). FC spaces could be provided with air lock door or be separated by double door compartment to avoid direct access from H2 hazardous zone to not-H2 hazardous zone. An air lock is not required if appropriate technical provisions are made (e.g. access to the space is not required and not made possible before the equipment inside is safely shut down, and the inside atmosphere is confirmed gas-free).

- FC spaces should be protected against external hazards such as adverse weather conditions, human interference, fires, and mechanical impact. FC rooms should be regarded as a machinery space of category "A" according to SOLAS chapter II-2 for fire protection purposes.

- FC spaces should be located in an area such that a fire or explosion in either will not (i) damage equipment in other compartments other than H2 system, (ii) damage the structural integrity of vessel that may cause flooding of water below the main deck or any progressive flooding. Specific CFD analyses are recommended to evaluate the consequences of hydrogen dispersion and explosion in FC spaces.

[3] MSC.1/Circ.1647 Interim guidelines for the safety of ships using fuel cell power installations.

- FC spaces and battery rooms should be located close to the vessel centreline or equally distributed in respect to the hull center of buoyancy.

- Distance between hydrogen storage areas and FC spaces should be minimized to reduce complexity of piping layouts.

5.3 Considerations for Material and component selection

5.3.1 Considerations for stack orientation

Water management inside the stack is a crucial aspect of fuel cell operation in maritime applications. Besides the normal operating conditions like flow rates, temperature and power the inclination on the ship due to wave motion influences how well water is removed from the stack. In case of non-optimal water management, the cells might become too dry or too wet, hindering the electrochemical reactions and therefore reducing power output. In light of these aspects the following points should be considered:

- The fuel cell stacks should be integrated in the system in a way that hydrogen and air outlets are pointing downwards for an optimum water removal.

- The fuel cell system, especially any components that deal with liquid water (e.g. water separator, humidifier) should be designed in a way that water removal and discharge can happen with the maximum inclination in all directions.

- If the fuel cell stacks can only be integrated on the ship in a way that hydrogen and air outlets are not pointing strictly downwards but are instead at an angle or parallel to the ground, the system should be designed in such a way that no water problem can occur due to inclination in any direction.

- If the fuel cell stack experiences power loss due to hindered water removal in any inclined position, the overall power of the system should be able to compensate for the reduced power, e.g. with adapted operating parameters.

- In case the influence of inclination on the fuel cell stack or system is not known, it should be tested at the maximum relevant angles in all directions.

5.3.2 Considerations for air filters

The catalyst layers of the fuel cell, where the electrochemical reaction take place, as well as the membrane are extremely sensitive to contamination, including organic compounds and metallic ions. As the cathode side is being supplied with air from the surroundings, special care should be taken to prevent degradation of the fuel cell. The marine environment represents especially detrimental conditions, foremost salt spray. Upon contamination with salt spray (among others) the performance of the stack might decrease significantly. Although a certain level of degradation might be reversible with special regeneration procedures, this cannot be guaranteed and with continued contamination the extent of irreversible degradation will increase. Thus, the following considerations should be addressed:

- Appropriate filters should be installed in the air intake to prevent contaminants from entering the fuel cell;

- Special consideration should be taken to prevent salt spray – water droplets with dissolved salt ions – from entering the air supply line of the fuel cell;

- If the effect of salt spray on the performance of the fuel cell is not known, it should be tested on representative stacks:

- Air intake filters should be redundant (in series), so that failure of one filter cannot damage the fuel cell. Additionally - if possible - also a monitoring of the air stream through the filters is advisable. With this measure a blocking may be detected in an early stage.

5.3.3 Considerations for material selection

Materials and components used in hydrogen-powered passenger vessels are critical for ensuring both safety and high-performance operation. These vessels, equipped with fuel cell systems, are especially vulnerable to contaminants from the marine environment and material degradation within the vessel. Specifically, contaminants from BoP (Balance of Plant) components—such as hoses, gaskets, and construction polymers—can negatively impact fuel cell performance and durability. This section examines the effects of contaminants from several commonly used materials: (1) FKM (Fluorine Kautschuk Material) hoses, (2) sulphur cross-linked EPDM (Ethylene Propylene Diene Monomer) hoses, (3) peroxide cross-linked EPDM hoses, and (4) POM-based polymers.

A MSC (multisinglecell) system, coupled with a hydrogen test station, was used to assess the impact of contamination on fuel cell performance. Unlike other studies that inject extracted contaminant compounds to the gas stream, this setup[4] allows for direct contamination of the fuel cell feed gases by materials or components at controlled temperatures, humidity, and flowrates, closely simulating real-world conditions. Additionally, the MSC setup enables simultaneous testing of up to six samples under identical conditions, making it a reliable method for comparing multiple samples.

The material and component evaluation protocol includes a series of measurements such as activation, slow steady-state degradation cycles at various temperatures (65 °C, 75 °C, 85 °C, and 95 °C), polarization curves at the end of each degradation cycle, and reactivation at the conclusion. Each measurement spans around 300 hours in total. The cell potential is continuously monitored to assess the performance of the fuel cell. Prolonged testing offers valuable insights into the durability of the materials under evaluation. For each test, a set of stainless-steel hoses, free from contamination, is used as a baseline reference.

For materials that cause significant contamination leading to performance degradation, additional heat treatment was conducted at various temperatures (100 °C, 130 °C, 175 °C, and 200 °C) and durations (0.5 and 20 hours) to assess the extent to which heat treatment mitigates contamination effects.

Key findings from this study are as follows:

- Sulfur cross-linked EPDM causes significant and irreversible contamination, leading to poisoning of the catalyst layers. Therefore, it is not recommended for use in fuel cell systems or hydrogen-powered passenger vessels.

- Peroxide cross-linked EPDM results in a high irreversible performance loss among without any pre-treatment. However, heat treatment at 130 °C for 20 or at 175 °C for 10 h hours nearly eliminates contamination completely from this material on the fuel cell making it suitable for the use in fuel cell system.

- FKM material causes moderate contamination and can be used without heat treatment. However, heat treatment for 20 hours at 130 °C reduces irreversible voltage loss by approximately 70%, and by ~83% after heating at 200 °C.

- POM (Polyoxymethylene)-based polymers have a negligible impact on the fuel cell performance, particularly on the anode side, and therefore are safe to be used in the fuel cell system.

- It is also recommended to minimize the amount of material used, as the performance drop caused by contamination is linearly proportional to the surface area of the materials in contact with the gases.

[4] Developed at VTT (Technical Research Centre of Finland).

5.4 Considerations for bunkering strategy definition

5.4.1 General considerations

5.4.1.1 General

The choice of hydrogen fuel FORM and STORAGE TECHNOLOGY depends on the energy requirements of the vessel. GH2 is typically cheaper to produce and requires less complex bunkering equipment. However, if the amount of fuel on board is high, GH2 becomes unpractical because of a lower volumetric energy density compared with liquid hydrogen. LH2 is therefore the suggested option for large vessels and vessels with larger range requirements.

Bunkering procedures and checklists as described within CCC 10/INF.16 report "Maritime Technologies Forum – Guidelines for the development of liquefied hydrogen bunkering systems and procedures" and/or the GUIDELINES FOR THE DEVELOPMENT OF LIQUEFIED HYDROGEN BUNKERING SYSTEMS AND PROCEDURES – JUNE 2024 should be considered when defining and planning the bunkering strategy.

5.4.1.2 Gaseous bunkering

Gaseous bunkering system protocol for ships can refer the existing standard (SAE[5] J2601-1) for land based heavy transportation as a reference for standard. However, some adjustments will have to be made for refuelling a ship instead of a land-based vehicle. Maximum allowable filling speed should be higher than mentioned 120 g/s in SAE J2601-1 to meet common bunkering operational times for shipping. Limiting factor for filling speed should be hydrogen temperature and pressure in ships tanks. The pressure should not exceed 1.25 the nominal working pressure of the tank. The temperature in the tanks should not exceed 85 ^{0}C when using type 3 or type 4 hydrogen tanks. The used refuelling protocol and H2 gas cooling approach should be adjusted to reach this target.

Gaseous bunkering procedures (land-to-ship) include but are not expressly limited to the following:

- Connecting ship to port and communication between ship and port staff;
- Connecting nozzle to ship using a loading arm or a hose and initiate the bunkering procedure;
- Data connection between ship and bunkering station starts automatically;
- Cascade bunkering automated by the filling station;
- End of bunkering and disconnecting nozzle;
- Disconnecting ship from the bunkering site and communication between ship and port staff.

5.4.1.3 Liquid hydrogen bunkering

Liquid hydrogen bunkering strategy is affected by the size and requirements of the vessel being refuelled. Based on the H2 storage capacity, for certain vessel it may be possible to use existing technologies and procedures for LH2 transfer with land-based hydrogen trailers. If the trailer is designed to use a pressure build-up loop as a method for LH2 transfer, the de-pressurisation of the trailer should be performed in a separate area to avoid safety concerns. Therefore, submerged LH2 pumps are recommended as a transfer method over a pressure build-up loop. For larger capacity bunkering scenarios, ISO 20519 can be referenced as a model for bunkering operations and procedures. The following land-based systems standards for LH2 bunkering can be relevant:

[5] SAE International is a global association of more than 128,000 engineers and related technical experts in the aerospace, automotive and commercial-vehicle industries. https://www.sae.org/

- ISO/TR 15916 for Basic consideration for the safety of hydrogen systems.
- ISO 13984:1999 on Liquid Hydrogen-Land vehicle fuelling system interface.
- ISO 19880-1, Gaseous hydrogen — Fuelling stations — Part 1: General requirements.

LH2 should be subcooled to reduce the need for gaseous hydrogen depressurization. This will require either a fixed land based bunkering station or a ship-to-ship bunkering vessel with chiller capacity on board.

Liquid hydrogen bunkering procedure from land-to-ship or a ship-to-ship is presented below:

Pre-bunkering

- Ship-to-bunkering station communication. Connecting one to another;
- Connecting the fill head between the bunkering station and the vessel, and initiate the bunkering procedure;
- Purge and leak testing;
- Stabilise the pressure required in the bunkering system. In case it is too high, the pressure should be relieved trough a discharge valve in a planned and safe way.

Bunkering

- Initial slow bunkering: cooldown of piping and bunkering with reduced speed. Pressure will rise in the beginning due to heat from the piping system. Pressure will then start dropping as more cool liquid is being pushed into the sip tank;
- **Main bunkering**: the pressure has reached the onboard LH2 system target value, bunkering speed depends on the system design;
- **secondary slow bunkering:** once the pressure starts approaching target value, the bunkering speed is reduced to prevent overfill;
- **End of bunkering**: upon reaching the target pressure, the bunkering will stop, and post-bunkering sequence will begin;
- **Post bunkering sequence**: after purge and leak testing, the dispenser unit will indicate that the bunkering has finished, and the nozzle can be detached from vessel and station, according to the approved bunkering procedures.

5.4.2 Final remarks

Gaseous and liquified bunkering operations regardless of the technical solution should have a planned and documented operation plan in compliance with existing rules and regulations. As per the LNG bunkering, this documentation should be maintained by the responsible vessel personnel.

There are very few experimental cases of hydrogen bunkering of ships to date. Further development is required for the transfer of large volumes of hydrogen between transfer stations and vessels. In such instances, on-site production of hydrogen should be explored to meet the maritime market demand and to make hydrogen as maritime fuel more attractive.

6 Methodological guidelines for applying the risk assessment at different design stages

The properties, characteristics and behaviour of hydrogen differ significantly from conventional fuels covered by current maritime international standards. For this reason, a risk assessment should be conducted to ensure that risks arising from the use of hydrogen, that may affect persons on board, the environment, the structural strength or the integrity of the ship are eliminated or mitigated.

It is suggested that the methodology for the risk assessment be based on a typical risk assessment process as described in MSC-MEPC.2/Circ.12 – Revised guidelines for FSA (Formal Safety Assessment) for use in the IMO rule-Making Process, which includes the processes of risk identification, risk analysis and risk assessment. However, ISO 31010 or equivalent can be acceptable.

For hydrogen ships, the Qualitative Risk Analysis (QualRA) should be supplemented with a comprehensive QRA (Quantitative Risk Assessment) in order to demonstrate that the level of safety is equivalent to conventional marine fuels.

6.1 Qualitative Risk Assessment (QualRA)

A Qualitative Risk Assessment for hydrogen fuelled ships should comprise, as a minimum, the following activities:

1. Scope. Definition of study basis and familiarization with the ship design;

2. HAZID. HAZID review with the purpose of identifying hazards and assess the risks using a risk matrix.

3. Report.

The HAZID is the core of the QualRA, and it is a combination of identification, analysis and brainstorming driven by a structured list of potential hazards, with the purpose of identifying all relevant hazards, their causes, possible consequences and mitigating measures included in the design.

The HAZID should consider the hazards associated with physical layout, operation and maintenance, following any reasonably foreseeable failure and it should cover at least the following spaces, zones and systems:

- TCS (Tank Connection Space);

- Enclosed or semi-enclosed fuel preparation rooms:

- Enclosed or semi-enclosed bunkering stations;

- Spaces where fuel enclosure units are installed;

- Spaces containing very high pressure or liquid hydrogen piping;

- Machinery spaces;

- Zones where vent lines and safety valve discharge lines are led;

- Escape and evacuation areas, as well as spaces where lifesaving equipment are placed (lifejackets, lifebuoys, etc.).

Another common form of qualitative assessment is a HAZOP (Hazard and Operability) studies or a FMEA (Failure Mode and Effects Analysis), that may also be used to demonstrate that any single failure will not lead to an undesirable event.

6.2 Quantitative Risk Assessment (QRA)

Once relevant hazards have been identified in the QualRA, the following stage of development be necessary to quantify the risk. This shall be performed with a Quantitative Risk Assessment (QRA) methodology which includes a systematic and complete assessment of the frequencies and the consequences of the events that can lead to a risk of fire or explosion. Subsequent definition of safeguards to bring all risk scenarios to ALARP (As Low As Reasonably Practicable) levels should allow a set of tangible measures to implement (physical barriers, alarms or other safety devices which are able to reduce either the consequence or the probability of a given hazard).

The main objectives of QRA study are:

- Quantify the level of safety risks (to people or property) associated with the operation of the ship.
- Demonstrate that the levels of risks are in compliance with risk acceptance criteria as agreed with authorities.
- Evaluate and select safeguards and risk reducing measures.

For hydrogen systems, analysis of gas dispersion, in case of leakage, has special relevance. In addition to gas dispersion analysis, Explosion & Fire Risk Analysis should be carried out to demonstrate that, an explosion or fire, in any space containing any potential sources of release and potential ignition sources should not:

- Cause damage or disrupt the proper functioning of equipment/systems located in any space other than that in which the incident occurs;
- Damage the ship in such a way that flooding of water below the main deck, or any progressive flooding occur;
- Damage work areas or accommodation in such a way that persons who stay in such areas under normal operating conditions are injured;
- Disrupt the proper functioning of control stations and switchboard rooms necessary for power distribution;
- Damage life-saving equipment or associated launching arrangements;
- Disrupt the proper functioning of firefighting equipment located outside the explosion-damaged space;
- Affect other areas of the ship in such a way that chain reactions involving, inter alia, cargo, gas and bunker oil may arise; or
- Prevent people access to life-saving appliances or impede escape routes.

Explosion & Fire Risk Analysis can also be used to evaluate the safeguards and safety parameters, as for example:

- maximum expected time between the pipe rupture and the leakage detection;
- time between the leakage detection and the gas supply shutoff;
- ventilation flow rate.

A typical methodology for risk level assessment based on a quantitative approach is reflected in ISO 19880-1.

Following the identification of the major hazards of a system or activity, the next step of performing the QRA is to estimate the frequency at which the hazardous events (or scenarios) may occur. The following are common techniques and tools available for frequency assessment are:

- Analysis of historical incident data;
- Fault tree analysis; and
- Event tree analysis.

The selected technique will depend on the availability of historic data and statistics.

In parallel with the frequency analysis, consequence modelling evaluates the resulting effects if accidents occur, and their impact on people, property and environment. Ignited flammable releases can result in a variety of consequences such as jet fire, pool fire, fireball or vapour cloud explosions depending on the type of scenario and time and place of ignition. The consequence assessment shall be carried out using recognized consequence modelling tools that are capable of determining the resulting effects and their impact on personnel, equipment and structures. These tools are normally validated by experimental test data appropriate for the size and conditions of the hazard to be evaluated.

6.3 Risk Criteria

The commonly accepted principle is known as the ALARP (As Low As Reasonably Practicable) principle. ALARP is a risk management principle aimed at ensuring that risks are reduced to levels that are “As Low As Reasonably Practicable”, taking into account factors such as available resources, technological feasibility, and societal values. It acknowledges that it may not be possible or feasible to eliminate all risks entirely, but efforts should be made to reduce risks to a level that is both tolerable and justifiable.

Risk criteria as usually expressed in individual and/or societal risk. The difference between the two expressions of risk is that location specific individual risk is used to show the geographical distribution of risk, while societal risk assesses the level at which areas with high population density are exposed to risk.

Individual risk is the risk of death for an individual who is present at a particular location, continuously throughout the year without wearing personal protective equipment. Individual risk is the frequency at which an individual is expected to sustain a given level of harm from the occurrence of the specific hazards.

Societal risk is defined as the (cumulative) frequency per year that a particular group of people dies concurrently as a result of accidents. Societal risk criteria have not been as widely used as individual risk criteria because the concepts and calculations involved are much more difficult.

The level of risk accepted for an individual depends on two aspects: (1) if the risk is taken involuntarily or voluntarily; and (2) if the individual has control over the risk or has no control. If an individual voluntarily exposes himself to a risk and/or has some control over it, then the level of risk that is accepted is higher than if the individual involuntarily exposes himself to the risk or has no control over it. This is especially important in a risk assessment for passenger or cruise ships, as a passenger on the ship has little or no control over the risks to which he is exposed by the ship and/or port activity. However, a ship's crew member has voluntarily chosen their place of work and, through their qualifications and training, has some control over the risks to which they are exposed at their place of work.

Examples of risk acceptance criteria can be found at *MEPC.2/Circ.12/Rev.2 Revised guidelines for formal safety assessment (FSA) for use in the IMO rule-making process* or *ISO/TS 18683 [6] Guidelines for safety and risk assessment of LNG fuel bunkering operations.*

7 Advancement and alignments with IGF code

7.1 Methodological considerations

This paragraph presents an alignment of the results of the e-SHyIPS project, as described in the previous paragraphs, with proposals over filling the gaps in the IGF code with relation to hydrogen as fuel. The IGF code contains 19 chapters with mandatory provisions for the arrangement, installation, control and monitoring of machinery, equipment, systems, and processes, using low-flashpoint fuels, focusing on liquefied natural gas (LNG).

The methodological steps to arrive to this alignment included:

a. The identification of gaps in the IGF code for H2 as marine fuel;

b. The development of experiments to generate new knowledge that addresses the gaps;

c. The proposal of advancements in the IGF Code based on e-SHyIPS research activities to fill the gaps.

This paragraph consolidates a presentation of the key findings and the proposals to fill gaps. Conclusions on IGF code updates can be derived through the review of the identified gaps, developed, and organized by IGF code chapter categories.

7.2 Identification of the gaps

This paragraph describes the considerations with regards to the identified IGF code gaps, which cover:

a) Considerations for goal update and general requirements;

b) Considerations for component suitability for H2 use;

c) Considerations of material suitability;

d) Considerations of special design features for safer H2 designs;

e) Considerations for risk assessment work;

f) Considerations for safety systems, operations, and controls;

The gaps are presented as follows, in summary:

- **Goals and risk-based design:** The functional goals in most of the code chapters are generated in accordance with LNG criticalities. Whereas H2 as fuel bears additional and higher risks. Therefore, the code needs proper readjustment of functional goals with regards to the minimum level of permissible leakages. Furthermore, criticalities of single faults onboard are higher than in land-based systems, which generates the need of requirements related to good housekeeping and minimum personnel exposure for H2 operations.

- **Arrangements and location**: Regarding arrangements and locations, the gaps include elements that affect the definition of chapter goals and general requirements, as well as proposals that affect design, safety systems and operation controls. Furthermore, reconsideration of the safety limits was described as gap, because the current definition of hazardous areas needs extension to include safety zones and barriers around H2 systems, including integrity maintenance.

- **Power conversion and redundancy:** In general, the IGF code includes requirements for redundancy of power systems, at cold or hot reserve. Because of the criticalities associated with high explosivity and flammability of H2, the design of redundancy systems requires update in terms of functionality, arrangement, and capacities. Furthermore, the code does not include references for the systems that relate to H2 energy conversion, e.g., fuel cells, reformers, or enrichment of fuel with H2, etc. The interim guidelines for fuel cells of IMO (MSC.1/Circ.164) is the most recent regulatory reference.

- **Fuel containment and quality:** With regards to fuel containment, gaps lie in the consideration of hydrogen fuel quality requirements, subject to the capabilities of the energy converters (fuel cells, H2 engines, etc.). Considerations on the types of containment systems and requirements that for dedicated use for H2 are also lacking.

- **Equipment and components:** Regarding equipment and components, most gaps relate to the assessment of existing systems' suitability and the inclusion of new design requirements, redefining the goals and functional requirements of systems that relate to bunkering, piping, fuel supply and containment. In example, gaps exist with regards to submerged pumps, over-pressure protection, ATEX requirements in the case of proxime electrical systems, and additional risk considerations in valve design against H2 permeability and explosivity.

- **Materials and manufacture:** H2 systems require suitable material properties and testing methods, to mitigate the risks related to H2 permeability, embrittlement, and H2 attack. The existing material requirement in the IGF code needs to get extended for H2 risks mitigation, describing new materials, manufacture requirements and testing methods. An example on materials testing requirements, e.g., for insulation or joints, is the assessment of fire resistance. An example on manufacture is that of welded joints, which are preferred where leaks cannot be tolerated.

- **Safety systems:** Regarding safety systems, there are several gaps in the code, related to H2 criticalities. Safety systems can either prevent the cause or the effect of a hazard. As an example, ventilation can prevent the development of an explosive environment, but cannot prevent a leak. A leak can be prevented with proper material testing.

The gaps address H2 leaks, Emergency Shut Down (ESD, Explosion Prevention and Ventilation, fire and Gas Detection, Fire safety systems, Hazardous event Propagation Avoidance, Extinguishing, labelling requirements, Pressure Relief, Safety System Arrangement, guidelines for component separation and monitoring, Inerting and Venting.

7.3 Advancements based on e-SHyIPS research activities

This paragraph summarizes findings of the e-SHyIPS project, which mitigate gaps as presented in the previous paragraph. The gap mitigation is based on considerations that resulted from e-SHyIPS research activities.

- ***Hull design and General arrangement considerations:*** *The level of re-design of a vessel for hydrogen propulsion is dependent on its size and application. When the hydrogen amount is significant a switch to LH2 system is recommended, even though this may require a complete re-design of the vessel. It's crucial to consider the vessel's size and the impact of H2 systems on general arrangement (GA), stability, hydrostatics, and hydrodynamics. Seakeeping calculations were performed to assess whether wave-induced stresses could affect fuel containment tanks and FCH systems. Virtual towing tank tests analysed the vessel's acceleration profile under wave conditions during bunkering and sailing. The study also compared liquid hydrogen tank sloshing effects with existing terrestrial transportation data, referencing hydrogen fuel cell inclination values from e-SHyIPS testing. Ship roll or pitch tolerance in rough seas depends on factors like ship size, type, design, and loading.*

    - *Seakeeping Simulations: Wave-hull interaction simulations show increased acceleration and roll responses in extreme wave conditions (high length, short period, and high speed).*

    - *Hydrogen Risks: Sloshing in LH2 tanks wasn't studied, but the DNV Handbook recommends a conditioning tank with a 3.5 bar inlet pressure and 5 bar equilibrium temperature to mitigate* *sloshing. All roll and pitch values align with FCH inclination tests from e-SHyIPS, meeting IACS (International Associations of Classification Societies) and SOLAS standards for propulsion machinery under rolling and pitching conditions.*

- *Leakage and rupture risks: For CGH2, a key risk is large hydrogen releases and tank ruptures, requiring CFD analysis to assess potential impacts, especially with top-deck storage. For LH2, leakage or tank ruptures on the lower decks pose risks of explosive clouds. Certified and inspected tanks and systems are essential, along with CFD analysis to evaluate explosion hazards.*

- ***Bunkering considerations:*** *The simulation results revealed the following considerations:*

  - *Consideration of measures to avoid pressure accumulation above operating limits. The simulation campaign of bunkering procedures for various filling rates indicated that pressure may accumulate in the case of an incoming saturated flow. The use of a liquefier and a pump to increase inlet pressure and sub-cool the liquid incoming flow, could be included in the considerations for mitigation measures for over-pressurization.*

  - *Consideration of a systematic to purge with hydrogen gas, to avoid risks of contamination, which accounts for the incoming properties of the flow: The simulation campaign demonstrated that the purging time depends on the incoming flow conditions.*

  - *Consideration of the impact of heat transport phenomena in case of distant loading (from land-based tank to the ship via pipelines), on the design of the system, including insulation for storage vessels and piping, liquefier to subcool the LH2 stream before bunkering, etc. The simulation campaign on pressure build-up during bunkering, indicated that BOG (Boil-off Gas) management measures could include vapor return line (where feasible), subcooling of incoming stream, and safe venting through properly insulated vent mast.*

- ***Machinery considerations:*** *The machinery simulation results revealed the following considerations for LH2 and GH2 fuelled machinery systems.*

  - *The design and sizing of power systems initially matched the nominal power of diesel engines, assuming a 100% hydrogen energy supply, but was later optimized for battery hybridization. Hybridization improved efficiency, reduced storage needs, and minimized fuel requirements, while maintaining performance equal to conventional power units. Two independent energy systems were included in different compartments, with the battery system separated from the fuel cell room. In hybrid configurations, the fuel cell may be designed to meet the mean power demand to prevent battery depletion during continuous operation.*

  - *Fuel consumption profiles were analysed for venting and dispersion calculations. The power split between fuel cell and battery may use either charge-sustaining or charge-depleting modes, with recharging at berth in the latter. FCH spaces were designed per the "Interim guidelines for safety of ships using fuel cell power installations" (MSC.1/Circ.1647) and IGF code chapter 5.5 to ensure gas-safe conditions. These spaces should have safety systems like detection, alarms, and mechanical ventilation to maintain under-pressure conditions, and CFD analysis is recommended for ventilation paths.*

  - *FCH spaces should be isolated from passenger areas to minimize risk, with air lock doors or double-door compartments to prevent hydrogen from escaping into non-H2 zones. These spaces should be protected from external hazards and meet fire safety standards as per SOLAS chapter II-2. They should be placed near the vessel's centreline and close to hydrogen storage to simplify piping layouts.*

- ***H2 storage system design and location:*** *The design of hydrogen storage systems for passenger vessels prioritized operational efficiency, safety, and regulatory compliance, guided by the IGF code and DNV's Handbook for Hydrogen-fuelled Vessels. Key strategies adopted in Phase 2 of the e-SHyIPS methodology included feasibility studies for bunkering frequency and strategy before conducting General Arrangement and stability assessments.*

    - *The design of hydrogen tanks considered factors such as type, size, refilling time, cost, material, and durability in marine environments. Redundancy is essential, requiring at least two independent fuel-containment systems to prevent single-point failures. Safety systems like detection, alarms, and shutdowns should be implemented. Hydrogen storage areas should be isolated from passenger compartments and protected against external hazards like fire, weather, and impact. Tanks should be positioned to minimize risks from collisions or groundings, while ensuring easy maintenance access and preventing damage to other equipment or structural integrity in case of fire or explosion.*

    - *Hydrogen tanks should be located near the vessel's centreline to balance their weight and minimize sloshing effect, with emergency discharge systems in place. For CGH2 tanks, open-deck placement is preferred for immediate ventilation, while LH2 tanks may be positioned on lower decks, with strict adherence to IGF 5.3.3 safety distances. Lower deck installations require robust ventilation to prevent gas buildup, and systems to manage boil-off gas (BOG) and control tank pressure, such as vacuum insulation or gas combustion units (GCUs). Minimizing the distance between storage areas and bunkering stations reduces risks, losses, and piping complexity.*

    - *One critical issue, especially in passenger ferries, is the proximity of the H2 storage system location as well as the fuel cell room to passenger compartments, where risks include hydrogen leaks leading to jet flames, asphyxiation, or explosions. Proper CFD analysis is recommended to assess the hydrogen distribution system design, such as to minimize hydrogen dispersion and explosion risks, along with appropriate venting strategies.*

- ***Emergency discharge process:***

    - *The emergency discharge system is designed to reduce onboard hydrogen during critical situations like fires, preventing tank rupture from heat exposure. Hydrogen's low ignition energy and wide flammable range make it prone to spontaneous ignition. While hydrogen usually deflagrates with low overpressure in open air, rare detonations have occurred, so the risk can't be ignored.*

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