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Fuel cell retrofits - safety and practical challenges

Electrification and Fuel Cells Development

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ABSTRACT

The International Maritime Organization (IMO) targets a reduction of the annual greenhouse gas (GHG) emissions from international shipping by at least 70% by 2040 compared with 2008 levels, and to reach net-zero by around 2050.

Given the average lifespan for the maritime deep-sea fleet is 20 to 30 years, it is highly likely that many ships currently planned or under construction will remain operational beyond 2050. To achieve the emission reduction targets, there will probably be no other possibility than retrofitting existing ships with technologies to operate on alternative fuels.

Fuel cell power installations can provide power on board ships for propulsion and auxiliary services, with high efficiency at zero to low carbon emissions by using hydrogen or other fuels with lower carbon intensity such as LNG or methanol.

Risks and hazards associated with fuel cell power installations are a major concern when considering a retrofit. For a safe integration of the fuel cells, the ship requires a major upgrade and additional installation of components and systems to meet the applicable safety requirements for fuel cells and the used fuel. For example, effective air supply and ventilation systems are crucial for fuel cell power installations to ensure a safe and reliable operation.

This study deals with safety and practical challenges related to fuel cell retrofitting. Possible retrofitting options and hazards associated with fuel cell power installations will be discussed. Requirements for fuel cell power installations on board ships will be elaborated on, based on class and regulatory requirements. Safety concepts for fuel cell spaces, in conjunction with air supply and ventilation requirements will be discussed in detail. Additional challenges related to fuel cell retrofitting to consider, such as hydrogen storage integration and fuel supply piping requirements, will also be discussed briefly.

1 INTRODUCTION

The International Maritime Organization (IMO) targets a reduction of the annual greenhouse gas (GHG) emissions from international shipping by at least 70% by 2040 compared to 2008 levels, and to reach net-zero by around 2050 [1]. Carbon pricing on shipping and other policies are being introduced to support and accelerate the industries' decarbonisation ambitions. From 2024 on, passenger and cargo vessels over 5,000 GT sailing to, from or between EU ports will be included in the Emission Trading Scheme (ETS) [2]. Additionally, the FuelEU Maritime Regulation sets specific targets for reducing GHG emissions from ships operating in EU waters; non-compliance will result in penalty fees [3]. The regulation allows to offset penalties of a complete fleet by having a few low- or zero-emission vessels. These measures will help to make currently expensive low-carbon fuels more attractive [4].

Given the average lifespan for the maritime deep-sea fleet is 20 to 30 years, it is highly likely that many ships currently planned or under construction will remain operational beyond 2050. A report by Lloyd's Register's Maritime Decarbonisation Hub highlights the importance of retrofitting to meet the net zero target by 2050, and it is highlighted that 20-30% of the ships that are built in the years ahead will need to undergo retrofits to operate on alternative fuels before 2050 [5]. It was also reported that up to 13,000 large merchant vessels could consider retrofitting with alternative fuels until 2030 to decarbonise [4].

Fuel cell power installations can provide power on board ships for propulsion and auxiliary services, with high efficiency at zero to low carbon emissions by using hydrogen or other fuels with lower carbon intensity such as LNG or methanol.

As the maritime industry is moving towards decarbonisation, fuel cell retrofitting can help Operators to meet increasingly stringent environmental regulations and reduce their carbon footprint. It can position Operators favourably to face future development and regulations in the industry. In addition, adopting fuel cells with hydrogen or other alternative fuels such as methanol or ammonia, can enhance a company's public image and align with its sustainability goals, which will be appealing to environmentally conscious customers and stakeholders.

This study deals with safety and practical challenges related to fuel cells. For a safe integration of the fuel cells, the ship requires a major upgrade and additional installation of components and systems to meet the applicable safety requirements for fuel cells and the used fuel. Requirements for fuel cell power installations on board ships will be elaborated on based on class and regulatory requirements. Configurations and arrangement possibilities for fuel cell spaces, in conjunction with air supply and ventilation requirements will be discussed in detail. Additional challenges related to fuel cell retrofitting, such as hydrogen storage integration and fuel supply piping requirements, will also be discussed briefly.

2 REGULATORY FRAMEWORK

The International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels (IGF Code) provides mandatory requirements for the installation and arrangement of machinery, equipment and fuel systems for ships other than gas carriers, operating with gas or other low-flashpoint fuels such as hydrogen [6]. By considering the characteristics of the fuel, it aims to reduce risks to the ship, its crew and passengers, and the environment. It covers prescriptive requirements for the use of natural gas (methane); however, for other low-flashpoint fuels such as hydrogen, an alternative design approach is required, where an equivalent level of safety has to be demonstrated. The equivalence of the alternative design needs to be demonstrated as specified in SOLAS regulation II-1/55 and is to be approved by the Flag Administration.

To assist Owners in navigating through the certification process for hydrogen-fuelled vessels with fuel cell power installations, Lloyd's Register (LR) employs the ShipRight Risk Based Certification (RBC) procedure to demonstrate that the risk from a design can be accepted and is equivalent with SOLAS Alternative Designs and Arrangements [7]. The RBC process, illustrated in Figure 1, consists of the following stages:

1 RBC-1: Design & Safety Statement.

2 RBC-2: Risk Assessment.

3 RBC-3: Supporting Studies.

4 RBC-4: Final Design Assessment.

5 RBC-5: Construction and In-Service Assessments.

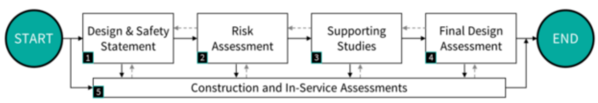

Figure 1. Illustration of the Risk Based Certification (RBC) process [7].

Table 1. Applicable LR Rules for the classification of ships retrofitted with fuel cells and hydrogen storage system, adapted from the Engine Retrofit Report 2023 [4] and modified for hydrogen as a fuel.

Design/equipment area	Goal of the rules	Rules applicable
Ship design and arrangement	To provide for safe location, space arrangements and mechanical protection of power generation equipment, fuel storage systems, fuel supply equipment and refueling systems	LR LFPF Rules Appendix LR3 Part A-1 5 Ship Design and Arrangement; otherwise LR LFPF Rules Part A-1 5 Ship Design and Arrangement
Fuel containment system	To provide that gas storage/fuel containment is adequate so as to minimise the risk to personnel, the ship and the environment to a level that is equivalent to a conventional oil-fuelled ship	LR LFPF Rules Appendix LR3, Part A-1, 6 Fuel containment system; otherwise LR LFPF Rules Part A-1 6.3 Regulations – General
Material and general pipe design	To ensure the safe handling of fuel under all operating conditions, to minimise the risk to the ship, personnel and to the environment, having regard to the nature of the products involved	LR LFPF Rules Appendix LR3 Part A-1 7 Materials and General Pipe Design; otherwise LR LFPF Rules Part A-1 7.3 Regulations for general pipe design; Rules for the Manufacture Testing and Certification of Materials, July 2022; LR Ship Rules, Pt 5, Ch 12 Piping Design Requirements;
Bunkering	To provide for suitable systems on board the ship to ensure that bunkering can be conducted without causing danger to persons, the environment or the ship	LR LFPF Rules Appendix LR3 A-1 8 Bunkering and LR LFPF Rules A-1 8.3 Regulations for bunkering station, 8.4 Regulations for manifold, 8.5 Regulations for bunkering system; LR LFPF Rules B-1 16.7 Testing regulations
Supply to consumers	To ensure safe and reliable distribution of fuel to the consumers	LR LFPF Rules Appendix LR3 A-1 9 Fuel supply to consumers; LR LFPF Rules A-1 9.3 Regulations on redundancy of fuel supply and 9.9 Regulations for compressors and pumps; LR Ship Rules, Pt 5, Ch 11 Other pressure vessels
Power generation including propulsion and other gas consumers	To provide safe and reliable delivery of mechanical, electrical or thermal energy	LR LFPF Rules Appendix LR3 A-1 10 Power generation including propulsion and other consumers,10.4 Fuel cell installations; LR Ship Rules, Pt 5, Ch 15 Steam Raising Plant and Associated Pressure Vessels and Ch 26 Fuel Cell Power Installations
Fire safety	To provide fire protection, detection and fighting for all systems related to storing, handling, transfer and use of hydrogen as fuel	LR LFPF Rules Appendix LR3 A-1 11 Fire safety; LR LFPF Rules A-1 11 Fire safety, and 15 Control, Monitoring and Safety Systems
Explosion prevention	To provide for the prevention of explosions and for the limitation of their effects	LR LFPF Rules Appendix LR3 A-1 12 Explosion prevention; LR LFPF Rules A-1 11.7 Regulations for fire detection and alarm system, 12.3 Regulations – General, 12.4 Regulations on area classification, 12.5 12.5 Hazardous area zones, and 15 Control, Monitoring and Safety Systems
Ventilation	To provide for the ventilation required for safe working conditions for personnel and the safe operation of machinery and equipment	LR LFPF Rules Appendix LR3 A-1 13 Ventilation; LR LFPF Rules Part A-1 13.3 Regulations – General, 13.4 Regulations for tank connection space, 13.5 Regulations for machinery spaces, 13.6 Regulations for fuel preparation room, 13.7 Regulations for bunkering station, 13.8 Regulations for ducts and double pipes, and 15.8 Regulations for gas detection
Electrical installations	To provide for electrical installations that minimise the risk of ignition in the presence of a flammable atmosphere	LR LFPF Rules Appendix LR3 A-1 14 Electrical installations; LR LFPF Rules A-1 14.3 Regulations – General
Control, monitoring and safety systems	To provide for the arrangement of control, monitoring and safety systems that support an efficient and safe operation of the fuel installations	LR LFPF Rules Appendix LR3 A-1 15 Control, Monitoring and Safety Systems; LR LFPF Rules A-1 15.3 Regulations – General, 15.4 Regulations for bunkering and liquefied gas fuel tank monitoring, 15.5 Regulations for bunkering control, 15.6 Regulations for gas compressor monitoring, 15.7 Regulations for gas engine monitoring, 15.8 Regulations for gas detection, 15.9 Regulations for fire detection, and 15.10 Regulations for ventilation;
Drills and emergency exercises	To ensure that seafarers on board ships to which these guidelines apply, are adequately qualified, trained and experienced	LR LFPF Rules Part C-1 17 Drills and Emergency Exercises may serve as a guidance
Operation	To ensure that operational procedures for the loading, storage, operation, maintenance and inspection of systems for fuels minimise the risk to personnel, the ship and the environment and that they are consistent with practices for a conventional oil- fuelled ship whilst taking into account the nature of these fuels	LR LFPF Rules Part C-1 17 Operations may serve as a guidance

The risk assessment is to evaluate risks related to the safe operation of the ship and as such is to address the safety of the fuel cell power installation itself and, where the fuel cell installation provides power for propulsion of the ship or other essential services, the dependability of the fuel cell power installation. The risk assessment studies consist typically of a hazard identification study (HAZID) during RBC-2, followed by supporting studies such as a failure mode effects and critical analysis (FMECA) in RBC-3 and a hazard and operability study (HAZOP) in RBC-4.

The IGF Code is incorporated into LR's Rules and Regulations for the Classification of Ships using Gases or other Low-flashpoint Fuels (LR LFPF Rules) [8]. These Rules also include requirements for ships using methyl/ethyl alcohol (Appendix LR1), ammonia (Appendix LR2), hydrogen (Appendix LR3) and liquefied petroleum gas (LPG; Appendix LR4) as a fuel.

In June 2022, the IMO published Interim Guidelines for the Safety of Ships Using Fuel Cell Power Installations (MSC.1/Circ.1647). It is expected that these interim guidelines will be added in a revised form to the IGF Code. Based on the final draft of these interim guidelines, LR developed Rules for fuel cell power installations and included them into LR's Rules and Regulations for the Classification of Ships (LR Ship Rules), Pt 5, Ch 26 Fuel cell power installations [9]; these Rules were released in January 2022. Roiaz et. al. provided a summary of the available statutory and class regulatory framework and tools applicable to the design implementing novel technologies and alternative fuels [10].

An overview of applicable Rules for the classification of a ship being retrofitted with a hydrogen fuel system and fuel cell power installations is shown in Table 1 with various design/ equipment areas being considered.

3 FUEL CELL RETROFITTING - GENERAL

3.1 Fuel cell power system

Several marine fuel cell power systems based on proton exchange membrane fuel cell (PEMFC) technology, with and without marine type approval certificates, are commercially available. Currently, these fuel cell power systems typically have a rated power output of only a few hundreds of kilowatts. Therefore, for large ships, it may require installing a large number of fuel cell power systems to meet their electrical power needs, depending if a partial retrofit or a complete retrofit shall be performed. Currently, larger megawatt-scale marine fuel cell power systems are under development and may be expected to become available within a few years from now. PEMFC systems may be equipped with a fuel reformer.

It is also expected that solid oxide fuel cell (SOFC) technology-based marine fuel cell power systems will be commercially available in the coming years, providing a fuel agnostic approach of enabling the use of current fuels, e.g. liquefied natural gas (LNG) or methanol, with the possibility to switch to using hydrogen in future, when a reliable hydrogen supply chain has been established.

3.2 Fuel cell power installation

Fuel cell power systems are installed and integrated on board together with additional components and systems (auxiliary systems), which are required for safe and efficient operation of the fuel cell power systems, and to reliably supply electrical power to the ship, forming the fuel cell power installation. The auxiliary systems of a fuel cell power installation may contain:

- Ventilation systems for fuel cell spaces and fuel enclosures;
- Power conditioning system for fuel cell current control and voltage conditioning, and connection to the ship's main switchboard;
- Thermal management systems for providing cooling to the fuel cell power systems;
- Inert gas supply systems for providing purging for gas-freeing and inerting services.

A schematic of a fuel cell power installation and its interfaces with the ship is shown in Figure 2a. A fuel cell power system may consist of multiple fuel cell power systems, electrically connected in parallel. Figure 2b shows an example, where the fuel cell power installation consists of eight fuel cell power systems, which are connected via a DC-DC converter to a common DC bus. A DC-AC converter connects the fuel cell power installation to the ship's main switchboard.

Where fuel cell power installations will supply power for propulsion of the ship or other essential services, the following requirements need to be complied with:

- Requirements relating to essential machinery and equipment in LR Ship Rules, Pt 5 Main and Auxiliary Machinery and the requirements for power supplies for main or emergency services of Pt 6, Ch 2 Electrical Engineering, Section 2 Main source of electrical power and Section 3 Emergency source of electric power need to be satisfied.

- Loss of any required auxiliary service, such as cooling water, is not to result in a loss of power for propulsion or other essential services.

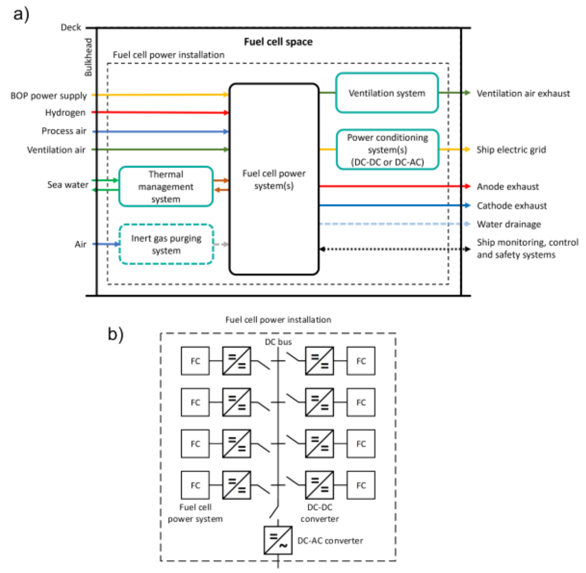

Figure 2. (a) Schematic of a fuel cell power installation including fuel cell power system(s), auxiliary systems and ship interfaces. (b) Schematic for electrical connection of multiple fuel cell power systems within a fuel cell power installation.

The design philosophy shall ensure that risk reducing measures and safety actions for the fuel cell power installation do not lead to an unacceptable loss of power. An unacceptable loss of power means that it is not possible to sustain or restore normal operation of the propulsion machinery in the event of one of the essential auxiliaries becoming inoperative, in accordance with SOLAS regulation II-1/26.3 [6].

As a result, where power for propulsion of the ship or other essential services is provided entirely by fuel cell power installations, the following requirements need to be complied with:

- At least two fuel cell power installations are to be provided so that one fuel cell power installation is retained in operation or is capable of being brought into operation in the event of a failure of the other.
- The power production capacity of one fuel cell power installation is to be such that in the event of any one fuel cell power installation being stopped, it will be possible to supply those services necessary to provide essential services necessary for propulsion and safety, as applicable.
- Means for blackout recovery and to bring the fuel cell power installation into operation from the dead ship condition without external aid.

Currently, there is no recognised international standard that provides safety-related requirements for the design, construction and operation of marine fuel cell power systems. LR's Fuel Cell Rules therefore require that the design of fuel cell power installations shall comply with industry standards, such as IEC 62282-2-100 Fuel cell technologies - Part 2-100: Fuel cell modules – Safety [11] and IEC 62282-3-100 Fuel cell technologies - Part 3-100: Stationary fuel cell power systems – Safety [12], or at least be equivalent to those standards acceptable to LR.

3.3 Retrofitting options

When considering the retrofit of a ship with fuel cells, various retrofitting options are available:

1 Additional power source: Installation of fuel cells as an addition to the ship's auxiliary power generators on board; the fuel cells can serve as a zero-emission power source when required, e.g. for operation in harbours;

2 Partial retrofitting: The ship's auxiliary power generators are partially replaced by fuel cells;

3 Full retrofit (auxiliaries only): Replacement of all auxiliary power generators by fuel cells in combination with energy storage systems (ESS); and

4 Full retrofit: Conversion from engine propulsion to electric propulsion and replacing main engine(s) and auxiliary power generators with fuel cells in combination with ESS.

The benefit of emission reduction from retrofitting ships with fuel cell power installation varies across ship types due to the technical challenges involves and the degree of retrofit that is feasible.

Figure 3 illustrates the different retrofit scenarios giving different emission reduction to technical challenge ratio for two target ship types, namely:

- Passenger ship with diesel-electric propulsion
- Cargo ship with diesel propulsion and auxiliary engines

The on-deck retrofit of the cargo ship (i.e containerised fuel cell power installation installed on-deck in addition to existing auxiliary engines) is easiest retrofitting with the lowest reduction in the emissions. This solution reduces emissions by reducing the number of running auxiliary engines, depending on the ship's operating mode (e.g. navigation, harbour, anchor, etc). It is considered at the lowest end of the “Technical Challenge” axis because it requires minimum ship structure modification and interfaces between the ship and fuel cell power installation, as well as the assumption, that the hydrogen storage may be installed on deck as well in a swapable configuration avoiding the need for bunkering installations.

The on-deck retrofit of passenger ship is not considered due to the lack of free deck area and aesthetic reasons.

A partial retrofit of the cargo ship (i.e. replacing one subset of the auxiliary engines with a fuel cell power installation (ESS may be optional in dependence on the power and energy management strategy) will offer a similar emission reduction benefit as the on-deck refit. This, however, is technically more challenging compared to an on-deck refit, as it requires modifications to the internal arrangements of the ship and its ancillaries.

The partial retrofit on the diesel-electric passenger ship poses a comparable technical challenge as with the cargo ship partial retrofit. However, it could also provide a higher emission reduction due to the possibility to replace a larger installed power (since the overall engines’ power is sized to also provide power for propulsion).

To achieve a corresponding emission reduction as the partial retrofit passenger ship, a full retrofit of the cargo ship (i.e. replacing all auxiliary engines with fuel cells power installations and ESS) will be required. This increases the technical challenges for the integration, power and energy management, and operations.

A full retrofit of the passenger ship (i.e. replacing all the engines by fuel cell power installations and ESS) will achieve the highest emission reduction but it is on the higher end of the “Technical Challenge” axis. In order to achieve the corresponding emission reduction as a full retrofit passenger ship, the cargo ship’s propulsion system will need to be converted to diesel-electric propulsion with fuel cell power installations and ESS in place of the auxiliary engines, hence this solution is on the highest end of the “Technical Challenge” axis.

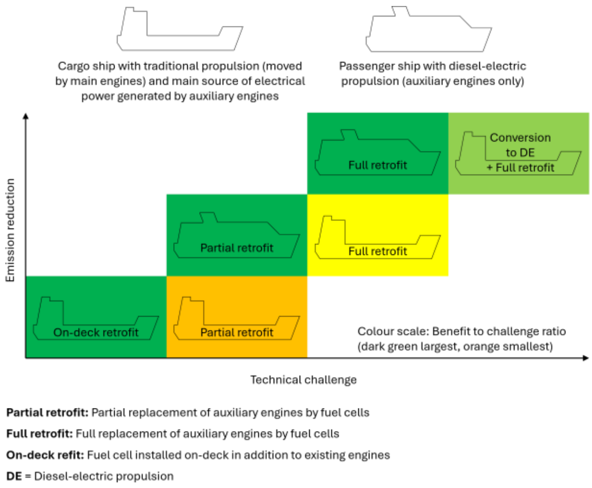

Figure 3. Visualization of the qualitative benefit achieved in emission reductions by fuel cell retrofitting versus the technical challenge of the fuel cell retrofitting.

LR Ship Rules require that where power for propulsion of the ship or other essential services is provided entirely by fuel cell power installations, no fewer than two fuel cell power installations are to be provided such that one fuel cell power installation is retained in operation or is capable of being brought into operation in the event of a failure of the other. Linking this to the fuel cell space safety concept, discussed in more detail in Section 4.3, this may lead to the requirement to provide two separated installation spaces for the fuel cells, which may increase the complexity of the fuel cell retrofitting of cargo ships.

Following a casualty that does not exceed a defined threshold, passenger ships are required by the Flag Administrations to be capable of returning to port under their own propulsion without having to evacuate passengers. The threshold is defined as the loss of the space of origin of a fire (for a fire casualty) or flooding of any single watertight compartment (for a flooding casualty). One possible solution to achieve compliance is by fitting two segregated and independent engine rooms (and power distribution systems, etc.). This solution could be advantageous in the case of partial retrofitting of fuel cells, e.g. by replacing the engines in only one of the engine rooms.

Fuel cells are typically supported by ESS, e.g. battery system, to enable fast transient load response and to allow the fuel cells to run at ‘optimal efficiency’ load. The required capacity of the energy storage depends strongly on the permissible ramp rates of the fuel cell and the load profile of the ship. PEMFCs have typically a fast load response, whereas SOFCs are slow; therefore, it may be assumed that a SOFC power installation requires a large energy storage installation compared to PEMFC power installation. In some arrangements and designs, e.g. a partial retrofit, the transient load response may also be provided from a remaining diesel-generator instead of an ESS.

The installation of a battery system on board requires a careful design and risk assessment; the requirements for their integration can be found in LR Ship Rules Pt 6, Ch 2, Section 12 Batteries [9], with additional requirements for lithium-ion battery systems.

An energy and power management system must guarantee the availability of sufficient energy to meet the main power demand in all operational scenarios. It should promptly alert Operators of any deviations from normal operation in the hybrid electrical power system and take immediate corrective measures upon detecting component faults that pose a danger, ensuring risks are reducted to an acceptable level. Additionally, the system should offer advanced functionality for control, monitoring, protection, and reliability of the hybrid electrical system beyond the scope of traditional power management requirements. Requirements for hybrid electrical power systems can be found in LR Ship Rules, Pt 6, Ch 2, Section 24 Hybrid electrical power systems.

The integration of fuel cells may require modifications of the ship's electrical system to ensure compatibility and operational efficiency, and may include adapting control systems, power distribution networks and energy management strategies to accommodate the different power generation characteristics of fuel cells. The interplay among combustion engines, fuel cells and battery ESS are to be addressed with a comprehensive and integrated approach. LR's Hybrid Power Class notation is assigned to ships whose main electrical power demand (i.e. the electrical power for maintaining the ship in normal operational and habitable conditions) is supplied by two or more different types of power source (e.g. engines and fuel cells) and/or by stored electrical energy (e.g. batteries).

The retrofitting of a diesel-electric ship with fuel cells may be considered easier than retrofitting a ship with traditional propulsion engines for the following reasons:

- Existing Infrastructure: Diesel-electric ships already have an established electrical system (including electric propulsion) that can be adapted to integrate fuel cells. This allows for a more straightforward transition since the electrical set-up is already in place to manage power distribution.
- Compatibility with Hybrid Systems: Diesel-electric systems are inherently compatible with hybrid configurations, where fuel cells can work alongside existing diesel generators. This allows for a smoother integration process, as the ship can continue to operate on diesel power while gradually transitioning to fuel cells.

Figure 4 shows simplified single line diagrams of a diesel-electric ship, with partial and full fuel cell retrofit. In the diesel-electric configuration (Figure 4a), four diesel generators (DG) are providing power to the ship's high voltage (HV) electrical grid; via transformers, the high voltage is converted to meet the needs of the low voltage (LV) ship's electrical grid. Two electric propulsion systems are connected via power conversion systems to the ship's high voltage electrical grid.

For a partial fuel cell retrofit, the single line diagram is shown in Figure 4b. Diesel generators 3 and 4 are replaced with a fuel cell power installation of equal rated power output. The fuel cell power installation is connected to the ship's high voltage electrical grid via a DC-AC converter system. An ESS is connected to the ship's high voltage electrical grid via a bi-directional DC-AC converter system for providing transient load response and to increase overall efficiency of the system.

For a full fuel cell retrofit, the single line diagram is shown in Figure 4c. All diesel generators are replaced with two fuel cell power installations, in order to fulfil the redundancy and dependability requirements discussed in Section 3.2. The fuel cell power installations are connected to the ship's high voltage electrical grid via DC-AC converter systems. Two ESS are connected to the ship's high voltage electrical grid via a bi-directional DC-AC converter system to provide improved transient response and to increase the system's overall efficiency.

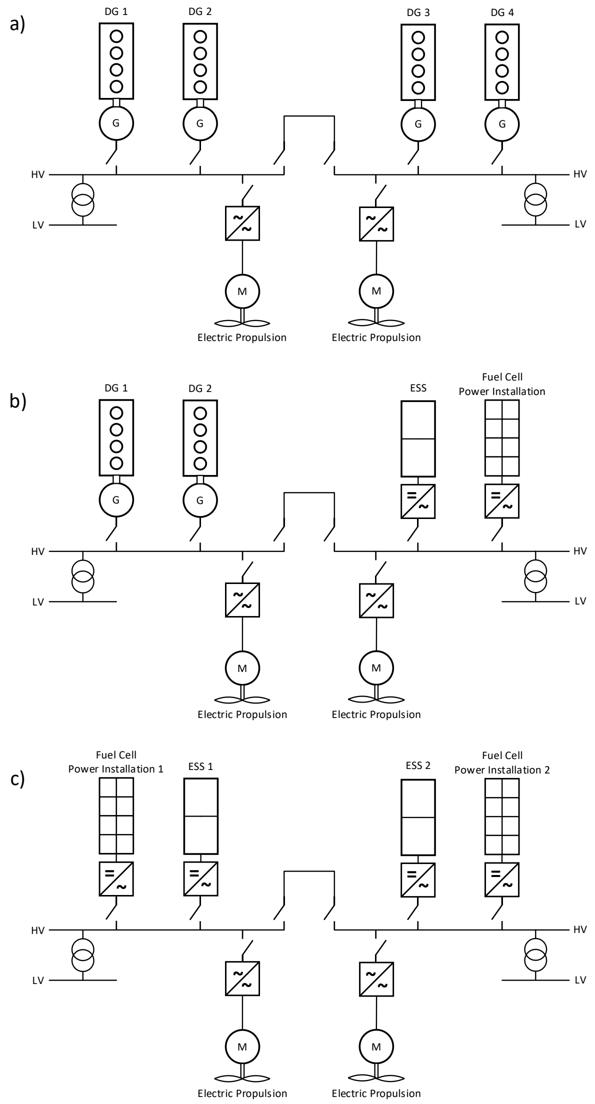

Figure 4. Simplified single line diagram of (a) diesel-electric (b) partial fuel cell retrofit and c) full fuel cell retrofit.

4 FUEL CELL RETROFITTING - SAFETY AND PRACTICAL CHALLENGES

4.1 General

The IMO requirements for vessels, including retrofits, using hydrogen as a fuel fall under the mandatory IGF Code. Therefore, a primary design challenge is to ensure that the systems and all subsystems comply with the goals and functional requirements outlined in the IGF Code Part A [6], such as:

- the safety, reliability and dependability of the systems shall be equivalent to that achieved with new and comparable conventional oil-fuelled main and auxiliary machinery;
- the probability and consequences of fuel-related hazards shall be limited to a minimum, through arrangement and system design, such as ventilation, detection and safety actions; and
- limitations of explosion consequences, e.g. an explosion in any space containing any potential sources of release and potential ignition sources shall not cause damage to or disrupt the proper functioning of equipment/systems located in any space other than that in which the incident occurs.

The installation and integration of fuel cell power systems, hydrogen storage and fuel preparation arrangements as well as their associated control and safety arrangements, present specific challenges for retrofitting projects [4], some of which are outlined below:

- Due to the shape and size of liquid hydrogen tanks, it needs to be assumed that in most cases, the old oil fuel tanks will remain inside the ship, unused, and the new hydrogen tanks will have to be installed on weather decks, or in the cargo hold, which most likely will lead to a decrease in cargo capacity. Hence, finding additional tank space while minimising the loss of cargo or passenger-carrying capacity is a major design challenge;
- Modification or replacement of fuel piping with effects on bulkhead penetrations across the vessel; and
- New and more demanding safety measures including ventilation, fire and explosion prevention.

For retrofitting, the hydrogen storage, fuel processing, piping, fuel cell power installations and safety measures need to be customised to an individual vessel layout, which creates challenges for the system integrator and requires a thorough design assessment process to ensure that the functional requirements are met by the design.

The focus of this paper is on the fuel cell power installation; however, in Section 4.5, additional challenges of fuel cell retrofitting, and switching to hydrogen as fuel, are being discussed in a wider context to create awareness of its complexity.

4.2 Hazards associated with fuel cell power installations

Fuel cells, while providing a cleaner alternative to conventional combustion engines, can introduce several hazards when utilised on ships. These hazards include:

- Mechanical hazards: an inadequate mechanical strength resulting from poor material specifications or improper geometric design can compromise the integrity of fuel cell power installation components, leading to potential failures that could endanger both the crew and the vessel.

- Electrical hazards: the stored electrical energy within fuel cells (remaining fuel cell voltage after shutdown) presents significant risks if not managed correctly, as unexpected discharges can lead to electrical shocks or fires, emphasising the need for robust safety protocols and equipment design.
- Thermal hazards: equipment overheating due to inadequate cooling or operational issues can result in unsafe conditions that may compromise the functionality of the fuel cell system, necessitating robust thermal management strategies.
- Gas hazards: a leak of flammable fluids from fuel cell systems can create significant fire or explosion hazards, making it critical to implement containment, ventilation, leak detection systems and proper handling procedures to mitigate risks.
- Fire and explosion hazards that arise due to fuel leakage, buildup of flammable/explosive mixtures and presence of ignition sources, require suitable fire and gas detection, alarm and fire extinguishing systems, as well as pressure relief arrangements on board.
- Malfunction hazards: failures in software, control circuits, protective safety components or other components within fuel cell power systems as well as auxiliary systems can lead to unsafe operational conditions, emphasising the need for rigorous testing and validation of these systems before deployment, and highlighting the importance of regular maintenance and testing to ensure system reliability.
- Human error hazards: erroneous human intervention during operation or incorrect maintenance of fuel cells can lead to hazardous situations if proper procedures are not followed, highlighting the need for comprehensive training, and clear operational manuals and guidelines.
- Ergonomic hazards: display design or location of visual alarm units can impede effective communication and response during emergencies, emphasising the need for clear and accessible information for Operators.
- Environmental hazards: extreme ambient temperatures, ship or wave-introduced vibrations, high heel angles or list can lead to unsafe or unreliable situations, emphasising the need for environmental testing to proof reliability of the fuel cell power system in marine environment.

Due to the unique properties of hydrogen, its introduction as a new fuel on board a ship presents significant safety challenges compared to traditional marine fuels, as its leakage can lead to serious fire and explosion hazards on board.

- Hydrogen atoms diffuse into metal leading to material embrittlement and may cause cracks and failures of the components that may lead to severe gas leakages.
- Due to the small molecular size, hydrogen is prone to leak through seals and joints. The leakage rate may be enlarged in marine environment. Especially in enclosed spaces on board the ship this can cause a significant safety risk as the leaked hydrogen may accumulate over time and form an explosive atmosphere.
- Due to the wide flammability range (4-75 vol.%) and a low ignition energy (0.02 mJ, in comparison to 0.29 mJ for methane), hydrogen can easily form explosive mixtures with air and is highly flammable; an electrostatic discharge is sufficient for ignition.
- Hydrogen flames are difficult to visually detect, as the flame emits light closely to the ultraviolet spectrum, not visible to the human eye. In addition, the low radiant heat impedes sensing, which may cause additional safety risks.
- Hydrogen burns at a very high temperature, which can make it difficult for conventional extinguishing agents to cool the flames effectively. Even after an initial fire is extinguished, residual hydrogen can reignite if it encounters an ignition source, posing a continuous risk.
- Hydrogen is a colourless and odourless gas; gas detectors at potential leakage points are essential to ensure the safety of the installation and the ship. The high buoyancy and fast dispersion of hydrogen may impede fast leakage detection.

If liquid hydrogen is being used, additional risks need to be considered.

- The extreme low temperature (-253°C) can cause cryogenic burns upon contact with liquid hydrogen or uninsulated equipment, and increase the risk of structural failures in storage and piping systems. In addition, condensable gases in the air, e.g. nitrogen and oxygen, can condense or freeze upon contact to liquid hydrogen or uninsulated equipment, which can lead to blockage of piping systems and related equipment.

- Leakages of liquid hydrogen can lead to a rapid gas expansion which can result in pressure bursts; in addition, in confined spaces, air may be displaced by the rapidly expanding hydrogen leading to the risk of asphyxiation for the crew in the affected space.
- Sloshing inside the liquid hydrogen tank may cause damage to the tank.

A risk assessment specific to fuel cell power installations is to be carried out for each installation on board. The risk assessment is to evaluate risks related to the safe operation of the ship and as such is to address the safety of the fuel cell power installation itself and, where the fuel cell installation provides power for propulsion of the ship or other essential services, the dependability of the fuel cell power installation.

4.3 Fuel cell space

4.3.1 ESD-protected fuel cell spaces

The emergency shutdown (ESD) protected fuel cell space concept is comparable to an ESD-protected machinery space as defined in Pt A-1, 5.4 Machinery space concepts of the LR LFPF Rules [8], and its design and arrangement needs to comply with the applicable requirements in LR Ship Rules, Pt 5, Ch 26, 4.9 Fuel cell space to 4.14 Fuel cell space - Inerting [9]. A schematic of this concept and space arrangement can be seen in Figure 5.

The fuel cell power system is installed in an accessible structural space having gastight A-60 boundaries and is equipped with gas detection, a ventilation system, and a fire detection and extinguishing system, together with corresponding ESD arrangements. Fuel supply piping may be single wall piping if the pressure is lower than 10 bar.

A single failure may result in a release of fuel or hazardous gases into the space, therefore the fuel cell space is considered as hazardous zone 1. Ventilation is designed to sufficiently dilute any reasonably foreseeable leakage scenarios due to failure. In the event of abnormal conditions involving gas hazards, ESD of the fuel cell power installation and its fuel supply, together with de-energizing any non-safe equipment and machinery within the space (ignition sources), shall be automatically initiated. Any equipment required to remain active for safety following detection of gas leakage, shall not be de-energized and shall be certified as suitable for hazardous zone 1. This may include ventilation system, gas and fire detection, general alarm systems and lighting.

Where an independent and direct access to the fuel cell spaces from the open deck cannot be arranged, access to fuel cell spaces is to be through an airlock compliant with the IGF Code 5.12 Regulations for airlocks. An airlock is not required if appropriate technical provisions are made such that access to the space is not required and not made possible before the equipment inside is safely shut down, isolated from the fuel system and drained of leakages, and the inside atmosphere is confirmed to be gas-free, or otherwise the space is considered non-hazardous under all conditions.

To comply with the requirements where power for propulsion of the ship or other essential services is provided entirely by fuel cell power installations, at least two fuel cell power installations in separated ESD-protected fuel cell spaces will be required. Depending on ship type and design, this may lead to difficulties in finding suitable space as well as extensive mechanical modifications of the ship's structure, e.g. separating the machinery space by adding corrugated bulkheads. In addition, the prescriptive requirements for gastight boundaries and the access to hazardous fuel cell spaces may add further design and technical challenges to the retrofitting of the ship.

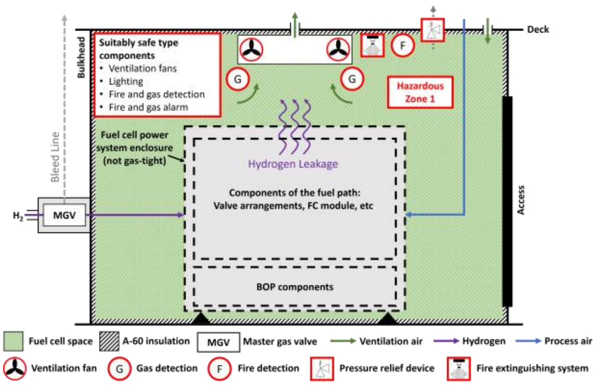

Figure 5. Schematic of a fuel cell power installation in an ESD-protected fuel cell space [13].

4.3.2 Gas-safe fuel cell spaces

The gas-safe fuel cell space concept is comparable to a gas-safe machinery space as defined in Pt A-1, 5.4 Machinery space concepts of the LR LFPF Rules. Currently, this concept is the most commonly applied by the maritime industry. A schematic of this concept and space arrangement can be seen in Figure 6.

Components of the fuel cell power system's fuel path, e.g. valve unit, piping, fuel cell module, etc., are contained in a gastight and ventilated (extraction type), or inerted, fuel enclosure, which acts as a secondary barrier in case of hydrogen leakage. Ventilation air for the fuel enclosure is taken from non-hazardous areas located outside the space. All fuel supply piping within the fuel cell space to the fuel cell power systems is double-wall piping.

The fuel cell space is considered gas-safe under all normal as well as reasonably foreseeable abnormal conditions, i.e. the spaces are inherently gas-safe. In an inherently gas-safe space, a single failure cannot lead to the release of fuel gas into the space.

The installation space of the fuel cell power system is equipped with regular machinery room ventilation, gas and fire detection, and a fire-extinguishing system.

Fuel cell power systems provided with a ventilated or inerted fuel enclosure provide the gas-safe arrangement, may be installed in machinery spaces. As there is probably no need for a physical boundary between two fuel cell power installations, if not otherwise identified in the risk and dependability assessment, it can be assumed that retrofitting a ship with fuel cell power systems in a gas-safe design is less technically challenging compared to installing fuel cell power systems in an ESD-protected fuel cell space.

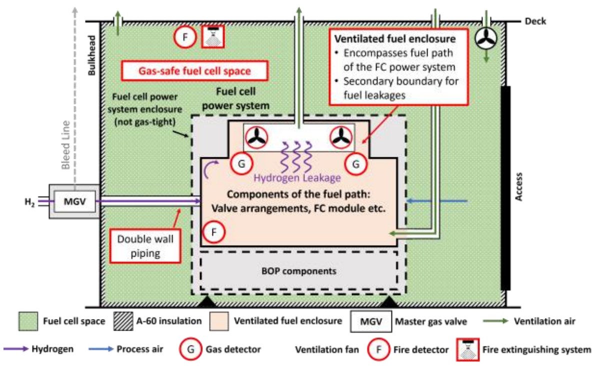

Figure 6. Schematic of a fuel cell power installation in a gas-safe fuel cell space; the fuel cell power system is equipped with a ventilated fuel enclosure and double-walled fuel piping is being used [13].

4.4 Machinery space ventilation vs fuel cell space ventilation

4.4.1 Machinery space ventilation

In traditional machinery spaces containing marine diesel engines for propulsion and power generation, the space ventilation serves two purposes:

- providing combustion air to the engines; and
- cooling the room by dissipating radiant heat from the engines and other heat sources.

ISO 8861; Shipbuilding—Engine Room Ventilation in Diesel-Engined Ships—Design Requirements and Basis of Calculations can be used to determine the air supply to machinery spaces, required by the engines for their combustion process and to remove heat from the machinery space [14]. At an ambient outside temperature of 35°C, the air temperature inside the machinery space may rise by a maximum of 12.5°C. For retrofitting with fuel cells, it would be beneficial to use existing ventilation and exhaust system arrangements for the fuel cell power installation to reduce design complexity, avoid the need for installing additional ducting and therefore reduce time and cost.

On gas-fueled ships, the machinery space ventilation may have an additional safeguard function against gas hazards. For example, in an ESD-protected machinery spaces of gas-fueled ships, a ventilation capacity of at least 30 air changes per hour shall be provided.

4.4.2 Fuel cell space ventilation

The utilisation of ventilation air being supplied to the fuel cell space differs significantly between ESD-protected and gas-safe fuel cell space arrangements and will impact the general process air supply and ventilation arrangement requirements.

The utilisation of space ventilation air for various purposes in machinery and fuel cell spaces is shown in Table 2. In ESD-protected fuel cell spaces the ventilation air provides cooling of the space and dilution of primary and secondary releases of hydrogen to levels below 25% of LEL. In gas-safe fuel cell spaces, the ventilation air is being used as process air to the fuel cell power systems and may also provide cooling to the space, especially in the case where power electronics or other heat sources are installed.

Table 2. Utilisation of space ventilation air for various purposes in machinery and fuel cell spaces.

Utilization of space ventilation air	Conventional machinery space	ESD-protected fuel cell space	Gas-safe fuel cell space
Combustion/ Process Air	Yes	No[1]	Yes
Cooling	Yes	Yes	Yes[2]
Dilution of leakages	Not required	Yes	No[3]

[1]needs to be provided via separate piping

[2]fuel enclosure ventilation provides most of the radiant heat dissipation

[3]needs to be provided to the fuel enclosure via separate ducting/piping

For fuel cell retrofitting, the existing ventilation systems on a ship may potentially be utilised, but several important considerations must be considered:

1 Compatibility: The existing ventilation system has to be compatible with the specific requirements for hydrogen handling.

2 Safety Standards: The ventilation system must meet safety standards and regulations for hydrogen use. This may involve modifications to ensure that it can effectively detect leakages as well as dilute and disperse hydrogen in the event of a leak.

3 Increased Airflow Requirements: Hydrogen systems may require increased airflow to maintain safe concentrations. The existing systems need to be assessed to ensure they can provide the necessary airflow rates or determine if upgrades are needed.

4 Hazardous zoning: The ventilation ducts, and the ventilation air inlets and outlets have the same hazardous zone rating as the spaces to be ventilated. This could lead to non-compliance with rules and safety standards, requiring modification of machinery and equipment.

Based on the above considerations, it can be concluded that for the gas-safe fuel cell space configuration, the machinery space ventilation may not require any modifications as the space is deemed gas-safe in all situations. Consequently, there should be no specific safety-related requirements for the ventilation arrangement in this scenario, and the existing machinery space ventilation may be used as it is.

For ESD-protected fuel cell spaces, the fuel cell space ventilation system provides an active layer of safety and there are several prescriptive requirements for fuel cell space ventilation in LR Ship Rules, Chapter 26 Fuel cell power installations, such as, diluting the average gas/vapour concentration below 25% of the LEL in all maximum probable leakage scenarios due to technical failures and at least 100% ventilation capacity redundancy upon loss of one fan. As the ESD-protected fuel cell space is considered as Hazardous Zone 1, it first needs to be verified that the ventilation ducting system is suitable for the conveying of exhaust ventilation air that may contain hydrogen, e.g. suitable materials, installed equipment, risk of gas ingress to other enclosed spaces etc. This includes also if the ducting is suitable for the required mass flow rates. Suitably safe-type extraction fans may then be added to the existing ventilation system, providing the safety functions to the fuel cell spaces as required by LR Rules.

In case that the existing machinery space ventilation system cannot be used for the fuel cell space ventilation, the installation of additional ventilation ducting is required, which increases complexity and cost of the fuel cell retrofitting.

The utilisation of the auxiliary engine's exhaust system for serving the fuel cell power installation may be considered, if an acceptable technical/safety justification similar to the utilisation of the existing machinery space ventilation system can be provided, and the required technical modifications are done to comply with the corresponding Rule requirements. The utilisation of the auxiliary engines exhaust gas system for various purposes of the fuel cell power installation is shown in Table 3. The exhaust gas system may generally be used to convey process exhausts of the fuel cell power installation to the outside the ship. For ESD-protected fuel cell spaces, the exhaust gas system may serve as an exhaust duct for the fuel cell space ventilation. For gas-safe fuel cell space arrangements, the exhaust of the fuel enclosure ventilation may be conveyed to outside the ship via the exhaust system. In both cases, suitably safe-type ventilation will need to be installed to the existing exhaust system. The utilisation of the existing exhaust system will reduce the need for additional piping and ducting and will reduce the complexity, time and cost of the retrofitting.

Table 3. Possible utilisation of auxiliary engine exhaust system for fuel cell power installation retrofitting.

Utilization purpose	ESD-protected fuel cell space	Gas-safe fuel cell space
Use for fuel cell exhaust conveying	Yes	Yes
Use for fuel cell space ventilation (ventilation exhaust)	Yes	Not needed[1]
Use for fuel enclosure ventilation (ventilation exhaust)	Not applicable[2]	Yes

[1]regular machinery space ventilation is being used
[1]fuel cell power systems are not equipped with fuel enclosure

Figure 7 is providing a simple schematic of the arrangements of air supplies and exhausts in machinery spaces equipped with diesel generators and of fuel cell spaces when retrofitted with fuel cells; it does not consider the positioning of the inlets and outlets for ventilation. Prescriptive Rule requirements exist for the process of installing them and the exhaust ventilation.

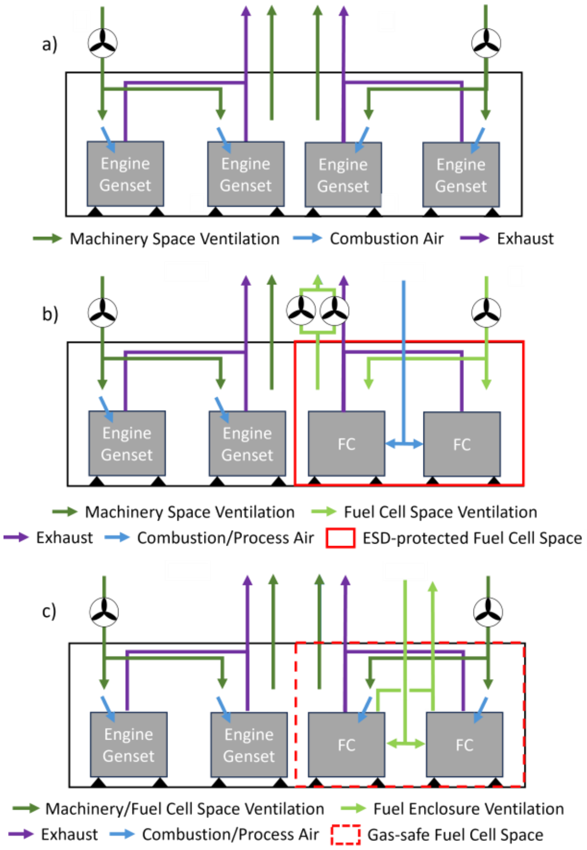

Figure 7. Schematic of air supply, ventilation and exhaust arrangements: a) Regular machinery space, b) ESD-protected fuel cell space, and c) gas-safe fuel cell space arrangement.

Figure 7a shows the schematic of the ventilation and exhaust system arrangement of a single machinery space containing four auxiliary gensets. Two supply fans provide ventilation and combustion air to the machinery space via duct arrangements. Ventilation air exits the machinery space through ducts and via the funnel to the outside of the ship. The extraction of the ventilation air from the machinery space may be supported by additional extraction fans, depending on the machinery space ventilation systems design and arrangement. The exhaust of two auxiliary engines is combined and routed to outside the ship via the exhaust gas system.

Two of the auxiliary gensets are being replaced by two fuel cell power systems with an assumed same power rating. The fuel cell power systems share a common ventilation (fuel cell space or fuel enclosure) as well as exhaust system, and are therefore considered as one fuel cell power installation. For this retrofitting scenario, it is assumed that the existing machinery space ventilation system and exhaust system can be utilised for serving the fuel cell power installation, hence reducing the complexity of the fuel cell retrofitting, and considered as a best-case scenario where only limited additional ducting or piping is required for the fuel cell retrofitting.

Retrofitting with ESD-protected fuel cell space arrangement (Figure 7b):

- The fuel cell power installation needs to be separated from the machinery space by a gastight boundary that has sufficient strength to withstand the effects of a local gas explosion, without affecting the integrity of the adjacent space and equipment within that space; this may require to insert additional bulkheads and suitable explosion pressure relief devices and ESD arrangements which increases the design challenges and complexity of the fuel cell retrofitting.
- The ship's ventilation system serving the fuel cell space was modified to comply with the requirements, e.g. by installing two extraction fans.
- Process exhausts of the fuel cell power systems are combined and conveyed to outside the ship via the reused auxiliary engines exhaust system.
- Additional process air supply ducting/piping needs to be installed and supplied directly to the fuel cell power systems because the fuel cell space is considered as hazardous zone 1, and process air needs to be taken from a non-hazardous area unless otherwise technically justified and validated by the risk assessment.

Retrofitting with gas-safe fuel cell space arrangement (Figure 7c):

- The fuel cell space is located within the large machinery space together with the diesel generators, without any physical boundary as separation; the whole machinery space is considered as gas safe.
- The ship's ventilation system is used as it is, providing cooling to the space, process air for the fuel cells, and combustion air for the remaining auxiliary engines.
- The exhausts from the fuel cell power systems are combined and conveyed to outside the ship via the reused auxiliary genset exhaust system.
- Additional extraction type ventilation with air intake from non-hazardous areas outside the space is required for the ventilation of the fuel enclosure of the fuel cell system (secondary boundary that contains any fuel leakage).

For both retrofitting scenarios, ESD-protected and gas-safe fuel cell space, additional piping/ducting will be required, at a minimum, for providing safety and functionality of the fuel cell power installation. Table 4 lists the required air supply and ventilation arrangements that need to be additionally installed when retrofitting a ship with fuel cells.

Table 4. Additional air supply, ventilation and exhaust arrangements at least required for fuel cell retrofitting.

Additional requirements	ESD-protected fuel cell space	Gas-safe fuel cell space
Process air supply	Yes	No[1]
Ventilation for secondary barrier ventilation	No	Yes
Process exhaust	Probably no[2]	Probably no[2]

[1]process air intake from the fuel cell space
[2]utilisation of engine exhaust system

The additional installation and routing of process air supply, ventilation and exhaust ducting through the existing ship structure and machinery spaces presents significant challenges. This complexity arises from the need to navigate around various structural components, equipment, and systems already in place. This may involve modifications to the ship's structure or machinery spaces, which can lead to increased costs and extended timelines for installation. Proper design and assessment of the ventilation system are essential to ensure compliance with safety regulations and operational efficiency.

ESD-protected fuel cell spaces may require less additional piping/ducting, however the requirement for gastight boundaries to adjacent enclosed spaces and the hazardous zoning of fuel cell space and ventilation ducting as Hazardous Zone 1 may be challenging. This could make the provision of a gas-safe fuel cell space more attractive despite the associated higher requirements for additional piping and ducting.

4.5 Additional challenges to consider

4.5.1 Hydrogen storage integration

While minimising cargo or passenger capacity losses as much as possible, sufficient endurance of the vessel needs to be achieved, which is equal to a certain amount of hydrogen stored on board.

A main challenge is to identify a suitable location for hydrogen storage that complies with regulatory requirements regarding the distance from the side shell plating, while also providing adequate space for venting and reliquefication systems.

For cargo ships, portable hydrogen tanks on deck may be considered, which is considered less technically challenging compared to under deck installation. Nevertheless, requirements such as mechanical protection of tanks depending on location and cargo operations, may lead to certain space restrictions and additional challenges related to hydrogen storage exchange procedures etc.

For under deck installations, the hydrogen fuel storage hold space shall be separated from the machinery spaces of category A, e.g. fuel cell spaces, or other rooms with high fire risks. The separation shall be done by a cofferdam of at least 900 mm with insulation of A-60 class. This requirement may impede random tank placement enormously.

Impacts on the vessel’s stability as well as loading condition limitation due to the location and weight of the installed hydrogen storage also needs to be investigated.

4.5.2 Fuel supply piping

Fuel piping and components containing hydrogen during normal or reasonably foreseeable abnormal operation are to be considered as Class I systems irrespective of the operational pressure in accordance with LR Ship Rules, Pt 5, Ch 12, 1.6 Classes of piping systems and component.

The routing of pipes through the existing ship structure and machinery spaces presents significant challenges. This complexity arises from the need to navigate around various structural components, equipment, and systems already in place. Careful planning and engineering are required to ensure that the new piping integrates seamlessly with the existing infrastructure while maintaining accessibility for maintenance and inspection. Additionally, considerations must be made for potential interference with other systems, such as electrical and ventilation, which may complicate the routing process further.

The diameter of the piping is a critical factor, especially when retrofitting existing systems to accommodate the larger mass flow requirements of alternative fuels such as methanol and ammonia due to their lower energy density. These fuels typically require larger pipe diameters compared to traditional fuels to ensure adequate flow rates and prevent pressure drops. In case of gaseous hydrogen piping, the lower energy density of hydrogen may be compensated by a certain degree by using higher gas pressure. However, in enclosed spaces, hydrogen supply piping from the tank connection space to the fuel cell power installation needs to be double walled, which will increase the overall diameter of the piping and therefore the space occupation. Liquid hydrogen has a higher volumetric energy density compared to gaseous hydrogen at common pressure levels, e.g. 35 to 70 MPa, therefore a smaller piping diameter may be expected. However, the required heat insulation around liquid hydrogen piping systems will probably also lead to larger overall space demand. If existing piping routes are utilised, additional space must be allocated for the layout to accommodate the increased volume. This may involve modifications to the ship's structure or machinery spaces, which can lead to increased costs and extended timelines for installation. Proper assessment of the available space and careful design of the piping layout are essential to ensure compliance with safety regulations and operational efficiency.

4.5.3 Ventilation and fuel tank venting system

Ventilation is essential for the safe operation of gas-fuelled ships for several key reasons:

1 Preventing gas accumulation: Gas-fuelled ships use gases such as hydrogen or natural gas, which can be hazardous if they accumulate in enclosed spaces. Proper ventilation helps to disperse any leaked gas, reducing the risk of explosion or fire.

2 Emergency response: In the event of a gas leak or other emergency, effective ventilation can facilitate quicker evacuation and response efforts by ensuring that hazardous gases are quickly dispersed.

3 Maintaining safe air quality: Adequate ventilation ensures that the air quality within the ship remains safe for crew members. It helps to dilute any harmful gases and maintain oxygen levels, which is crucial for the health and safety of those on board.

4 Temperature control: Ventilation systems help regulate the temperature within the ship, particularly in areas where gas is stored or used. This is important for maintaining the integrity of the gas systems and preventing overheating, which could lead to safety hazards as well as performance reduction of fuel cells.

Unless protected by inert gas, permanently installed ventilation is required in:

- closed or semi-enclosed bunkering stations;
- ducts and double-walled pipes (non-vacuum insulated);
- tank connection spaces;
- fuel preparation rooms;
- machinery spaces (and fuel cell spaces); and
- any spaces as identified as part of the risk assessment process.

These requirements lead to a large amount of ventilation ducting required to be added to the ship. Like piping, this may require modifications to the ship's structure or machinery spaces in order to be able to incorporate the large volumes of required ventilation ducting.

A fuel tank vent system is required for gas-fuelled ships primarily for safety. The venting system helps to safely release any excess gas or vapours that may accumulate in the fuel storage tanks; this prevents the risk of explosion or fire due to gas build-up.

Proper venting ensures that pressure remains within safe limits, preventing structural damage to the tanks and piping system.

The venting is to be routed to a safe location on open deck which will introduce additional hazardous zoning and may impede the placement of ventilation and air inlets.

4.5.4 Fire detection, prevention and control

The invisible flame mentioned in 4.2, high flame temperature and reignition risk make hydrogen fires particularly hazardous and challenging to manage.

A fixed fire detection and fire alarm system complying with the International Code for Fire Safety Systems (FSS Code) shall be fitted in all spaces containing potential sources of flammable fuel leakage and ignition. The fire detectors shall be suitable for hydrogen; for the selection of suitable fire detectors, ISO/TR 15916 Basic considerations for the safety of hydrogen systems can be taken into account.

Fast gas leakage detection and fuel supply isolation may prevent fire and explosion. Therefore, permanently installed gas detectors need to be installed amongst others in tank-connection spaces, ducts around fuel piping and machinery spaces containing gas piping, gas equipment or gas consumers. The required gas safety system and safeguards add complexity to the ships control, monitoring and safety system.

Water- or CO2-based fire-extinguishing systems may be used; initiation shall occur after isolating the hydrogen source to avoid the risk of reignition. Manually operated water spray systems shall be provided for cooling, fire prevention, and crew protection, and shall cover escape routes and hydrogen storage tank(s) located on open decks.

The existing fire detection and extinguishing system of the ship will need to be replaced with systems and arrangements suitable for hydrogen fires. Additional structural fire protection (A-60) is required for fuel cell spaces, which will probably increase the weight of the ship, potentially affecting its stability, buoyancy and overall performance. This necessitates careful engineering assessments and may require additional design changes or structural modifications. As ships have limited space, integrating A-60 fire protection may require the reallocation of existing machinery/spaces or the redesign of layouts, which can be logistically challenging.

5 CONCLUSIONS

Ship retrofitting with alternative fuels and new technologies such as fuel cells is essential for achieving emission reduction targets of the IMO. Ships may be retrofitted with fuel cells ranging from simple on-deck installations of fuel cells as an additional zero-emission power source to a full retrofit including conversion from engine propulsion to electric propulsion.

Hydrogen, a promising alternative fuel enabling zero-emission power production, has a number of safety-critical properties such as its wide explosive range and the low energy levels required for ignition energy, which makes the prevention of gas and explosion hazards a major concern for the retrofitting.

LR has developed Class Rules for ships using fuel cells and alternative fuels such as hydrogen, which include both functional and prescriptive requirements.; These requirements seek to achieve an equivalent level of safety, reliability and dependability of the systems as is achieved by those with conventional oil-fuelled main and auxiliary machinery installations.

In this work, safety and practical challenges related to fuel cell retrofitting were discussed, and the following findings were elaborated:

- Safety and practical challenges will vary in dependence on the scale of retrofitting (partial retrofit vs full retrofit) as well as the target vessel.
- Retrofitting ships with diesel-electric propulsion systems to fuel cell electric propulsion is considered less complex compared to converting ships with traditional engine propulsion, due to the established electrical system (including electric propulsion that will ease fuel cell integration and operation).
- Gas-safe design and arrangement of fuel cell power installations (gas-safe fuel cell spaces) is considered beneficial for retrofitting purposes, due to the absence of hazardous zone inside the space and related relaxations regarding equipment protection, possibility for location inside machinery spaces without additional boundary, as well as the possibility of using existing machinery space ventilation systems.
- Reusing existing machinery space ventilation and exhaust system for the fuel cell power installation will reduce the need for integrating additional ducting and piping and reduce overall complexity and cost of the retrofitting. However, material compatibility, safety standards and requirements, and eventually the impact of hazardous zoning needs to be considered.
- Additional technical challenges that need to be considered for retrofitting include the integration of the hydrogen storage, fuel supply piping, ventilation and venting requirements, as well as additional requirements for fire detection, prevention and control.

6 DEFINITIONS, ACRONYMS, ABBREVIATIONS

DG: Diesel generator

ESD: Emergency shutdown

ESS: Energy storage systems

ETS: Emission Trading Scheme

FMECA: Failure mode effects and critical analysis

FSS Code: International Code for Fire Safety Systems

GHG: Greenhouse gas

HAZID: Hazard identification study

HAZOP: Hazard and operability study

HV: High voltage

IGF Code: International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels

IMO: International Maritime Organization

LNG: Liquefied natural gas

LR: Lloyd’s Register

LR LFPF Rules: LR's Rules and Regulations for the Classification of Ships using Gases or other Low-flashpoint Fuels

LR Ship Rules: LR’s Rules and Regulations for the Classification of Ships

LV: Low voltage

PEMFC: Proton exchange membrane fuel cell

RBC: Risk Based Certification

SOFC: Solid oxide fuel cell

7 REFERENCES AND BIBLIOGRAPHY

[1] International Maritime Organization, 2023. *2023 IMO Strategy on Reduction of GHG Emissions from Ships*, Online available: https://www.imo.org/en/OurWork/Environment/Pages/2023-IMO-Strategy-on-Reduction-of-GHG-Emissions-from-Ships.aspx/ [Accessed: 8th January 2025].

[2] Lloyd's Register, 2024. *What is the EU ETS and EU MRV?*, Online available:https://www.lr.org/en/services/statutory-compliance/ eu-ets-and-eu-mrv/ [Accessed: 8th January 2025].

[3] Lloyd's Register, 2024. *Preparing for FuelEU | Navigating the Maritime Energy Transition*, Online available: https://www.lr.org/en/expertise/maritime-energy-transition/fueleu-regulation/ [Accessed: 8th January 2025].

[4] Lloyd's Register, 2023. *Engine Retrofit Report 2023: Applying alternative fuels to existing ships*, Online available: https://www.lr.org/en/knowledge/research-reports/2023/applying-alternative-fuels-to-existing-ships/ [Accessed: 8th January 2025].

[5] Lloyd's Register, 2021. *First movers in shipping's Decarbonisation – a framework for getting started*. Online available: https://www.lr.org/en/knowledge/press-room/press-listing/press-release/2021/first-movers-in-shippings-decarbonisation-a-framework-for-getting-started/ [Accessed: 8th January 2025].

[6] International Maritime Organization, 2016. *International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels (IGF Code)*, Online available: https://www.imo.org/en/publications/Pages/Home.aspx [Accessed: 8th January 2025].

[7] Lloyd's Register, 2024. *ShipRight Design and Construction - Risk Based Certification (RBC*), Online available: https://www.lr.org/en/knowledge/shipright/procedures/ [Accessed: 8th January 2025].

[8] Lloyd's Register, 2024. *Rules and Regulations for the Classification of Ships using Gases or other Low-flashpoint Fuels*, Online available: https://www.lr.org/en/knowledge/lloyds-register-rules/rules-and-regulations-for-ships-using-gases-or-low-flashpoint-fuels/ [Accessed: 8th January 2025].

[9] Lloyd's Register, 2024. *Rules and Regulations for the Classification of Ships*, Available online: https://www.lr.org/en/knowledge/lloyds-register-rules/rules-and-regulations-for-the-classification-of-ships/ [Accessed: 8th January 2025].

[10] Roiaz, M. et al. 2022. Classifying the Innovation: The Certification of New Designs for Power Generation, Conversion and Energy Storage Focusing on the Reduction of Ships Emissions. *Progress in Marine Science and Technology - Technology and Science for the Ships of the Future*, 6: 563–270.

[11] International Electrotechnical Commission, 2020. *IEC 62282-2 Fuel cell technologies - Part 2-100: Fuel cell modules – Safety*, Online available: https://webstore.iec.ch/en/publication/59780 [Accessed: 8th January 2025].

[12] International Electrotechnical Commission, 2012. *IEC 62282-3-100 Fuel cell technologies - Part 3-100: Stationary fuel cell power systems – Safety*, Online available: https://webstore.iec.ch/en/publication/59566 [Accessed: 8th January 2025].

[13] Lloyd's Register, 2025. *Guidance Notes on the Installation of Fuel Cells on Ships*, Online available: https://www.lr.org/en/knowledge/lloyds-register-rules/guidance-notes/guidance-notes-on-the-installation-of-fuel-cells-on-ships/ [Accessed: 8th January 2025].

[14] International Organization for Standardization. 1998, *ISO 8861:1998 Shipbuilding — Engine-room ventilation in diesel-engined ships — Design requirements and basis of calculations*, Online available: https://www.iso.org/obp/ui/#iso:std:iso:8861:ed-2:v1:en [Accessed: 8th January 2025].

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