STASHH

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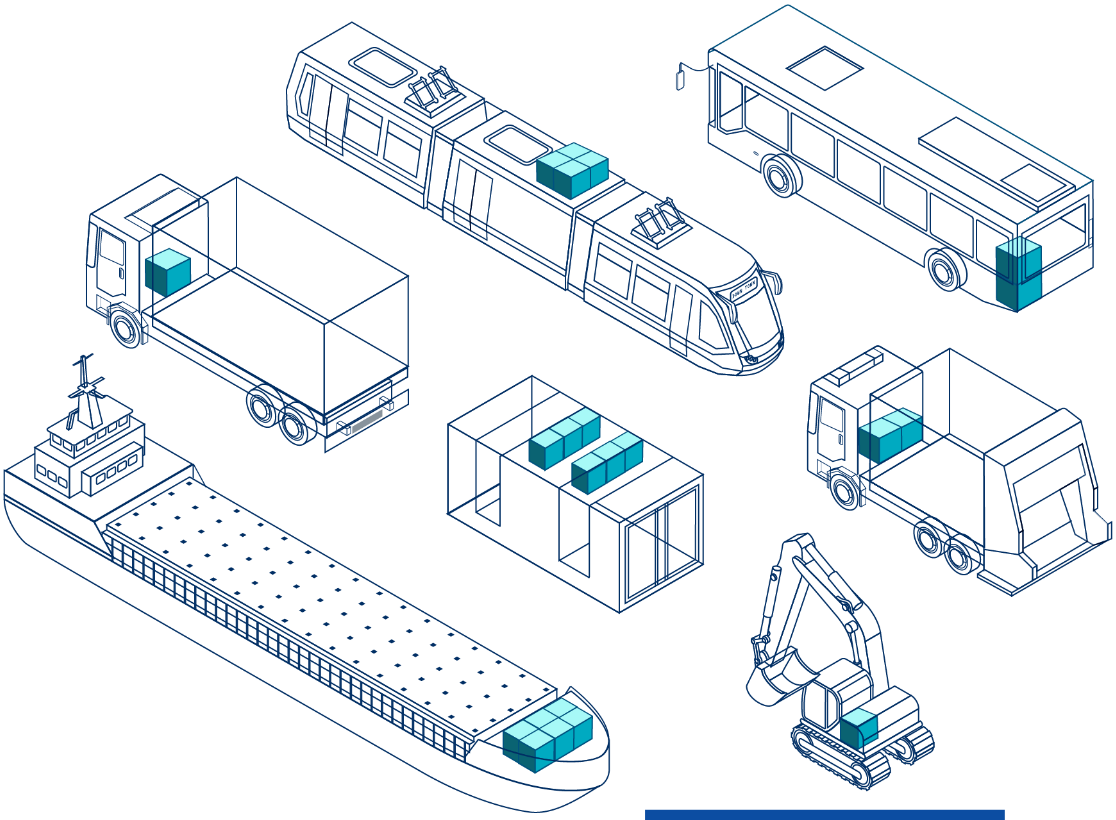
OEM integration of standard FCM



Clean Hydrogen Partnership

Co-funded by
the European Union

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STASHH

Towards a standardised fuel cell module

Clean Hydrogen Partnership

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1 Introduction

1.1 Document overview

Task 3.6 as defined in the StasHH proposal:

Damen will lead the consortium's OEMs to provide their experience in defining best practices for integration of the StasHH standard FCMs into their applications. OEMs will provide experience from their specific field in regard to safety, cooling system, air and hydrogen feed, and integration with pre-existing electrical and control systems.

1.2 StasHH objectives

Figure 1 presents the overall objectives of the entire project. This tasks directly relates to:

- <u>Integration:</u> Identify the interfaces between the standard FCM and the different applications. Check whether there are gaps in terms of functionality and/or regulations.
- <u>Scalability to 1MW:</u> In this task parallel operation of multiple FCM will be studied since this is required for multiple applications.
- <u>Lower RD&I for OEMs:</u> The resulting deliverable of this tasks will provide a steep learning curve about the integration of the FCM. This will prevent re-engineering.

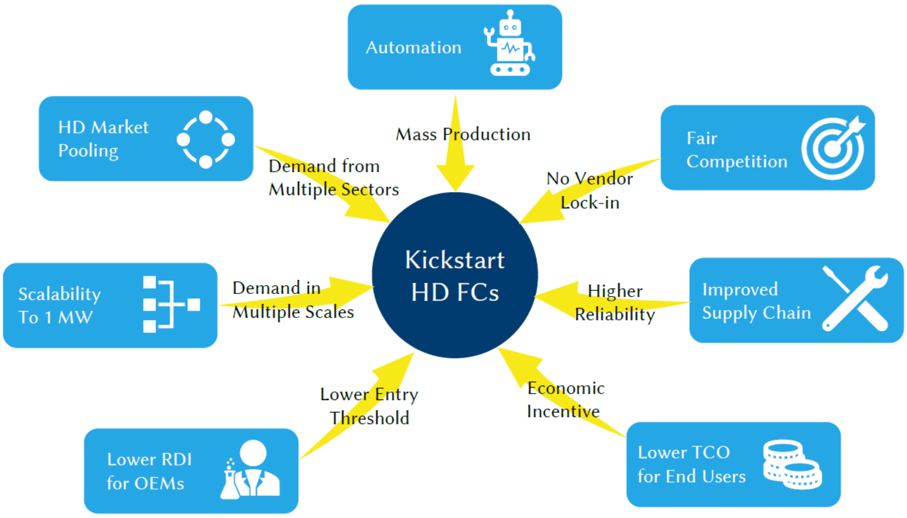

Figure 1: StasHH' specific objectives and their contribution to the overall objective

1.3 Tasks ambitions

The following ambitions are defined for this task:

- Correct implementation of the fuel cell modules for the various applications.
- Opportunity for OEM's to get more insights in the adoption of the fuel cell modules.
- Interaction with the fuel cell manufacturers about their product and possible target market.

1.4 Scope of task 3.6

This report describes the best practices for implementation of the Fuel Cell Module standard. The standard is targeted for the following applications:

- Off-Road
- Rail
- Road
- Stationary
- Water (maritime)

The interfaces and support systems for all these applications will be described. The previous deliverables within WP3 have quantified the interfaces. This deliverable will go in more depth to qualify the interface, which could lead to different preferences between applications. FCM could benefit from this insight to optimize the standard for a specific application.

1.5 Responsibilities

Damen is responsible for this document, with the support of the OEMs and input of the FCM suppliers in this project. Table 1 presents for each application the (expected) supporting OEM.

Table 1: Overview of OEM partners in relation to the applications

Application:	**OEM partner:**
Off-Road	VDL and Volvo
Rail	Alstom
Road	AVL, FEV, Solaris and VDL
Stationary	VDL ES
Maritime	Cetena, Damen and FPS

2 Key-Terminology and StasHH goal

The StasHH project's paramount objective is to standardize the sizes of the fuel-cell (FC) module. The FC module is defined as the FC Stack and the Balance-of-Plant (BoP) components. The BoP consists of (at least) the air-supply system, the cooling system, the hydrogen recirculation system and the control system. Excluded are the hydrogen storage, the cooling radiator(s), the expansion tank, the filters, the exhaust (all of which are meant to be part of the vehicle) and the DC/DC converter. The DC/DC converter can optionally be integrated into the module. The FC module will act as subordinate and follow the requested power or current asked by the vehicle control system. The module must be intrinsically safe.

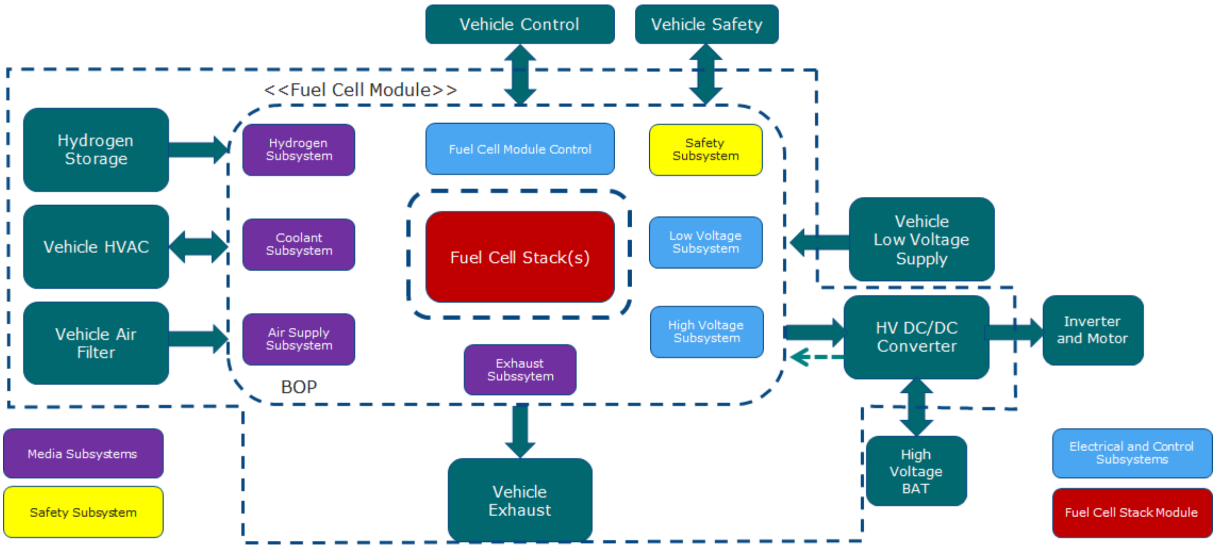

Figure 1: Key Terminology

The goal of WP3 in the StasHH project is to define the:

- Standard Size (outside)	(D3.2 chapter 3.2)
- Interface area(s) (incl. position)	(D3.3)
- Hydraulic and pneumatic interfaces	(D3.3)
- Electrical interfaces	(D3.3 and D3.4)
- I/O communication	(D3.4)

The StasHH definition should be a kind of overall specification that can be used by any OEM in any application. A high rate of interchangeability between the FC module manufacturers is the ultimate goal.

3 Interfaces

This chapter is the core of this report. It will elaborate on all the interfaces of the fuel cell with the foreseen applications.

3.1 Physical arrangement

The outside dimension of the FCM are well defined. However, dependent of the application the FCM will be placed in various places and orientations.

3.1.1 FCM position

For most applications it seems that the FCM will be placed outside or in a semi-enclosed space. However, for the maritime application it is most probably in an enclosed room. The placement of the FCM will have consequences towards the safety philosophy. This brings the following considerations:

- IP rating of the FCM needs to be high for outside installation to protect the inside components from the environmental conditions. The environmental conditions also contain application specific conditions, like sand or dust for off-road applications. While for an enclosed installation the IP rating can probably be lowered, since the enclosed space will give more protection.
- Installation of a FCM in an enclosed space gives worries regarding possible leakages which could cause hydrogen accumulation inside the enclosed space. A possible solution would be to actively ventilate the FCM towards the outside of the enclosed space, so hydrogen will not leak into the enclosed space. For outside installation natural ventilation seems sufficient as long hydrogen can move freely upwards without any obstructions, like a trailer for a truck.

3.1.2 FCM orientation and inclination

The FCM will be placed in all kind of orientations. First preference for the (off-)road and rail seems to be flat, while for the stationary and maritime application an upward position is favorable. For the latter applications the installation space is typically larger, so there is more attention for maintenance and accessibility. Also, it’s expected these installations will be larger, so more modules interconnected.

Inclination is also an important topic. Almost all of the applications seem to have specific operations where inclination will be present. For road and rail one can think about driving up- and downhill. While off-road machines might tilt due to heavy lifting. For the maritime application inclination is important due to waves, but also special manoeuvres with ships, like an emergency turning circle or escorting tugboat.

3.1.3 Movements, vibrations and shock

Since the FCM are intended for the heavy duty applications, such as stone crushers and construction equipment, severe operational conditions can be expected. Ships are prone to the induced vibrations of the propeller and slamming waves, while (off-) road applications have to find their way through potholes. Also trains experience quite some shock due to rail switches. It is difficult to exactly specify these conditions. Possible alternative solution could be to resiliently mount the FCM. Figure 2 shows two specific examples for illustration.

Figure 2: Two examples of heavy duty equipment with high impact on the fuel cells. The above picture shows a ship sailing in heavy waves with shock and movements as a result. Below a container terminal with heavy shocks due to loading and a dusty atmosphere.

3.2 Hydraulic and Pneumatic connections

This chapter describes the hydraulic and pneumatic interfaces of the FCM. Different options are described to connect a single FCM. Also considerations are presented in case of a larger system with multiple FCM.

3.2.1 Cooling system

The standard describes a coolant subsystem within the FCM. However, the FCM manufacturer decides on the execution of this functionality. This will also be influenced by the choice for an integrated DC/DC converter or not. Anyhow, for this part, it is assumed the cooling water pump is included in the FCM. Also, the by-pass loop to regulate the cooling capacity is assumed part of the FCM.

For most of the applications with a single or few FCM installed, the cooling system will be quite straightforward. Especially, in case of a liquid/air heat exchanger directly connected to each separate FCM, see Figure 3.

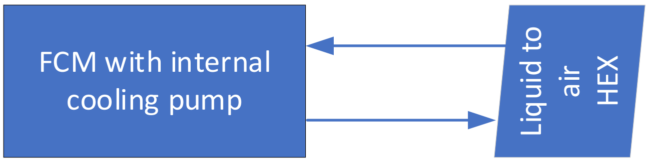

Figure 3: Direct cooling with liquid to air heat exchanger

The same principle could be applied for the maritime application, but surrounding water instead of air will be used as a cooling medium, see Figure 4. The internal cooling water pump characteristics are required to engineer such a system. This principle could be limited due to distance between the FCM and HEX. On ships the distance might become too large in order to have sufficient flow. Also when the number of FCM are getting large, it will get difficult to install the external heat exchangers.

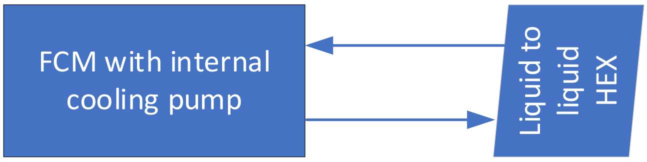

Figure 4: Direct cooling with liquid to liquid heat exchanger

Due to the expected limitations of a direct cooling circuit for the maritime application, a secondary circuit could be added. This could be a closed or open circuit, see Figure 5 and Figure 6. The secondary circuit could be shared by multiple FCM, so a single secondary circuit for multiple primary heat exchangers. The primary heat exchangers will probably be installed in the fuel cell room. The external pump will probably be installed near the secondary heat exchanger or sea water inlet in another space.

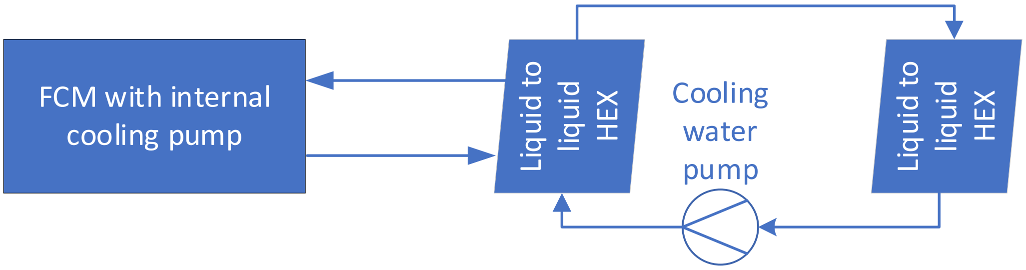

Figure 5: Cooling water circuit with a secondary closed system

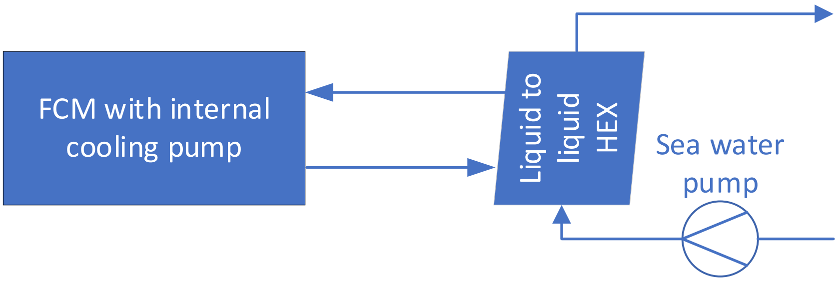

Figure 6: Cooling water circuit with a secondary open system

The secondary cooling circuit adds complexity towards the cooling system. One can also imagine that a larger system might require many primary heat exchangers. However, it seems like it is possible to connect the different internal cooling systems in series as well, see Figure 7. The parallel connection is preferred in terms of cooling efficiency compared to the connection in series. Overall, a lot of piping is required and proper documentation is missing. Especially related to the internal cooling pump.

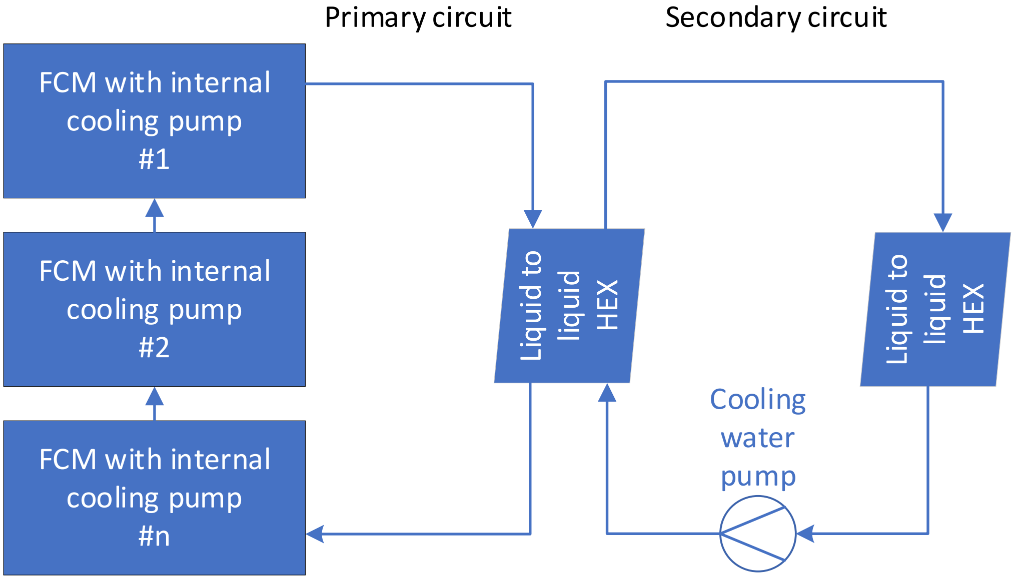

Figure 7: Primary cooling water circuit in series connection

3.2.2 Inlet air and exhaust air

The FCM have to withstand different conditions, depending on the application. In general, the fuel cell has to be able to perform at outside air temperatures between -20 deg C and 45 deg C, and a maximum humidity of 85%. The process air entering the fuel cell stack needs to be clean. Various undesired particles should be removed from the air, like dust, salinity and/or exhaust gasses from nearby combustion engines. Also, the intake temperature and humidity are of importance. When the environmental condition deviates, measures should be taken. Also, the air has to be cooled after compression.

For a system with multiple FCM, it could be considered to combine the air intake. This means one filter connected to multiple FCM’s. Filter capacity would be the main consideration for this option, but it could potentially save quite some piping. For FCM installed in an enclosed space, the intake air of the space could also be filtered. This would eliminate the air intake piping, but requires more filter capacity since also the space ventilation will be filtered.

The exhaust of a FCM contains a high level of water vapour. In order to handle the vapour carefully, a condensate trap is required in the exhaust, which removes condensed water from the exhaust. Otherwise the FCM performance will reduce due to increase of exhaust back pressure. Overall, the exhaust needs to be designed to the best practise. Next to that, a thermal module can be used to recover water and recover heat from the exhaust stream. Some FCM suppliers provide an additional thermal module for this.

The acidity of water produced in the fuel cell is quite low and can contain local pollutants, such as (traces of) heavy metals or PFAS. For maritime, it is unclear if the drain water can be released into the environment or needs a pretreatment. An analysis report of the water composition should be provided by the fuel cell suppliers according to [Lloyds].

[IMO] prescribe a hazardous area 1 for the FC exhaust gas and process air of 3 meters. [Lloyds] also addresses the requirement of hydrogen detection in the exhaust piping. Keeping the exhaust pipes separate for each FCM would make it easier to detect the faulty FCM when hydrogen is detected. Hydrogen contamination risk of the air intake has to be reduced by placing the inlet opening as far as possible from the outlet, preferably lower than the outlet since hydrogen will rise. The inlet air needs to be supplied from a location that does not contain any contaminated air.

For all applications, the FCM exhaust air can be combined with the FCM ventilation outlet. In maritime industry, the exhaust air and ventilation outlet of the FC space can be combined according to [IMO]. So only if the FCM is considered as FC space both ventilation outlet and exhaust air can be combined.

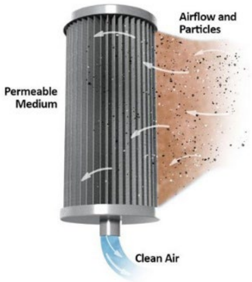

Figure 8: Example of air filtering. Source: Solberg.

3.2.3 Hydrogen supply

For all the applications, the hydrogen quality is equal, and the hydrogen storage system is assumed to be compressed hydrogen. The maximum storage pressure differs for each application, but is lowered in the distribution system. All the applications have the storage system arranged outside with natural ventilation.

The supply pressure depends on the requirements of the FCM supplier. For automotive higher pressures are common, since it allows a passive hydrogen circulation solution inside the FCM at a pressure of about 22 bar. This solution reduces weight and complexity, so lowers chance of failure. However, safety wise, low pressures are desired, because it would limit the leakage rate in case of a pipe rupture. Typical hydrogen supply pressures with a circulation pump are 6 till 12 bar.

For all applications it is desirable to purge the hydrogen from the FCM in the distribution system when it is powered off. This will reduce the risk on leakages, hydrogen slip and unintended reactions within the FC stack. Most of the FCM seem to have a function to slowly consume the left over hydrogen in the distribution system, so no external purging system will be required. For maritime, [Lloyds] is still in favor of a purging system to minimize risks after an ESD.

From maritime, fully welded pipes are recommended as much as practicable possible. Also, double wall piping is prescribed for enclosed installations. For the final FCM connection it seems more pragmatic to use a flexible metal hose with threaded connections. It’s not known if this would be allowed. Therefore, it is desired to have optionally a connection for double wall piping. A common fixed supply line could be used with multiple connections towards the FCM’s. The complication would be hydrogen detection in the FC room without knowing the exact source when a hose or other single walled piping is applied. Resulting in a complete shutdown of the FC system installed in the room.

Figure 9: Example of a flexible metal hose with different connections. Source: Hy-Lok

3.2.4 FCM ventilation

FCM ventilation should ensure a low concentration of hydrogen in the FCM in case of leakage. Also it helps removing hydrogen when a leakage is detected and the FCM is powered off. This reduces the safety risks. From the available documentation it becomes clear, not all the FCM have an active ventilation option. Also the location of the fan is not described. For (off-)road, there is a risk of getting dirt in the FCM, which therefore requires a filter to prevent this.

In maritime industry, the FCM ventilation requires monitoring and redundancy (at least two ventilators) when the FCM is considered as FC space installed in a gas safe space, see Figure 10b.

3.2.5 Enclosed space ventilation

This subparagraph is specific for the maritime application, since it is the only application with the FCM's installed in an enclosed space. It also seems the hardest interface to tackle, which is being further complicated by the multiple regulatory frameworks for various shipping segments and areas, e.g. inland and seagoing vessels. For none of these segments regulation is in place, but preliminary guidelines are released.

However, all of these regulatory framework pursue the double barrier protection principle. This indicates that all possible hydrogen leakages are covered by a secondary safety zone, e.g. a double walled pipe. The outer pipe functions as second barrier and leakage detector. In case of a failure of the inner fuel line, the outer pipe makes sure no dangerous situation (explosive atmosphere) will occur. A common feature of the second barrier is an exit point towards a safe location. The second barrier and the safe location are therefore ATEX zones. A typical solution for the second barrier is high rate ventilation, so the hydrogen concentration stays below the Lower Explosion Limit (LEL) in case of a leakage. Another option is to fill the secondary barrier with an inert gas.

This short background steers towards the following solution directions:

1. The enclosed space is the second barrier. However, this probably will result in infeasible high ventilation rates for the enclosed space. This is caused by the properties of hydrogen, a very low LEL and density.
2. The enclosed space will be filled with inert gas. This has as drawback that the enclosed space cannot be entered. Also nitrogen should be available onboard in case of some slippage.
3. The FCM housing acts as secondary barrier. This could also being achieved by ventilation or fill with inert gas. Probably this might require changes to the FCM designs, but seems the most pragmatic solution. Mind, the other interfaces also need to comply with the double barrier principle, like a double walled hydrogen supply.

Most of the above directions are part of the Guidance notes on the installation of fuel cells on ships of [Lloyds], see Figure 10.

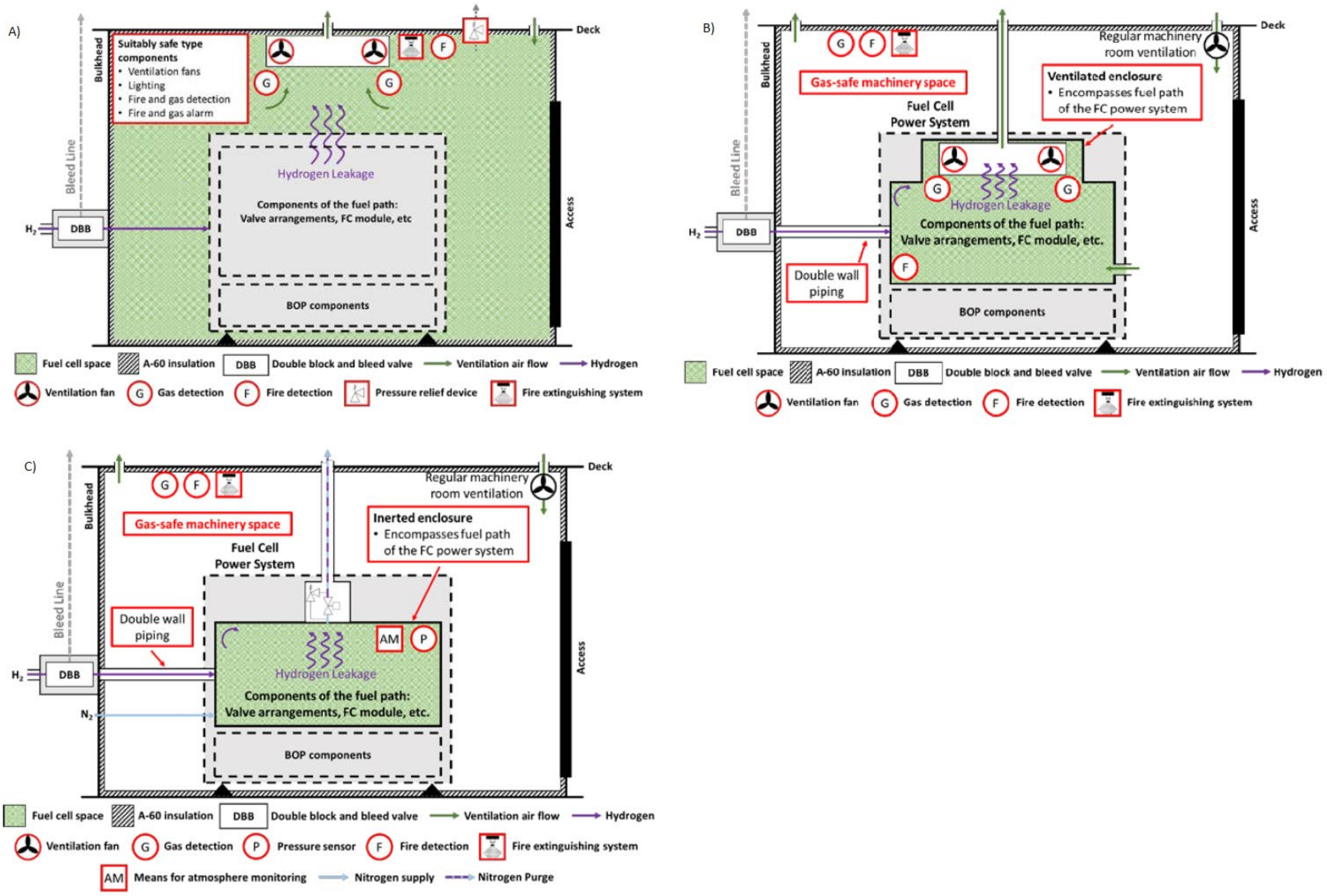

Figure 10: three accepted configurations of the fuel cell room & space. A) the fuel cell room is the fuel cell space, leaked H2 has to be vented by 2 fans, B) the FC module is the fuel cell space, which has to be vented by 2 fans. The room itself requires regular machinery room ventilation. C) the fuel cell room is gas safe and the fuel cell space (the FC module) has to be pressurized with an inert gas, which is the safest option

The fuel cell space should be treated as hazardous zone 1 and therefore all electrical equipment should be certified for zone 1 according to IMO MSC.1/Circ. 1647 2.1.1.3 and 4.2.3. However, the fuel cell stack itself is not considered a source of ignition if the surface temperature is kept below 300 degrees Celsius under every condition. This however only applies to the maritime industry; the other industries don't consider any hazardous area, except for during maintenance.

3.3 Electric and control

3.3.1 Electrical

In the maritime application case, the fuel cell modules' power must be distributed at a main switchboard. Multiple units must be connected in parallel, and in parallel with other sources as well, including battery systems. Various configurations of DC power systems onboard vessels are possible which give rise to different topologies of connections. In this application the focus will be on DC switchboards with a voltage below 800V. Two main system variants are possible, namely a floating bus where the DC voltage is directly determined by the state of charge of the connected battery system, or a fixed bus where DC/DC converters interface batteries (and all other sources) to a fixed voltage system. These are also termed passive or active DC systems respectively (according to IEC TR 63282), reflecting the regulation control of the DC voltage via power electronic converters. Additional requirements from classification society require overcurrent (short circuit and overload) protection on the electrical system and connected branches. This gives rise to certain requirements which must be taken into account when integrating fuel cell modules into maritime power systems. Figure 11 shows the conceptual integration of a fuel cell system into a maritime application on a fixed bus system. Here an FCM with integrated DC/DC converter is assumed. Figure 12 shows the setup with a non-integrated DC/DC converter. Third party converters are here provided, integrated inside the main switchboard.

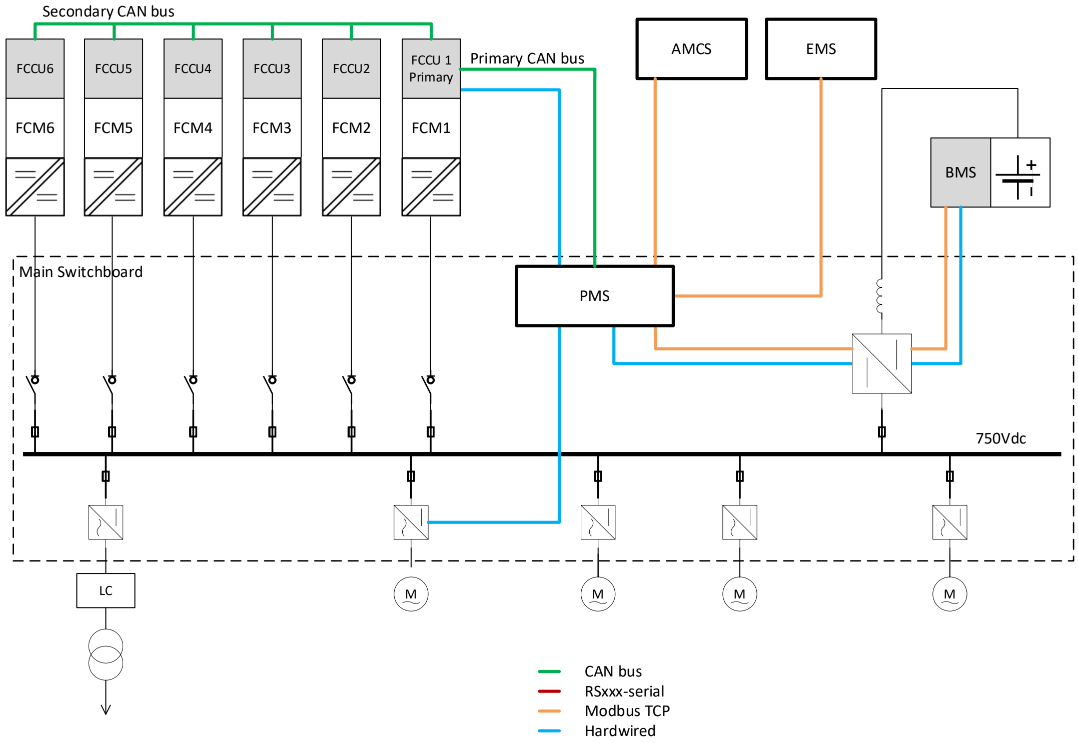

Figure 11 Multiple fuel cell integration in fixed bus system.

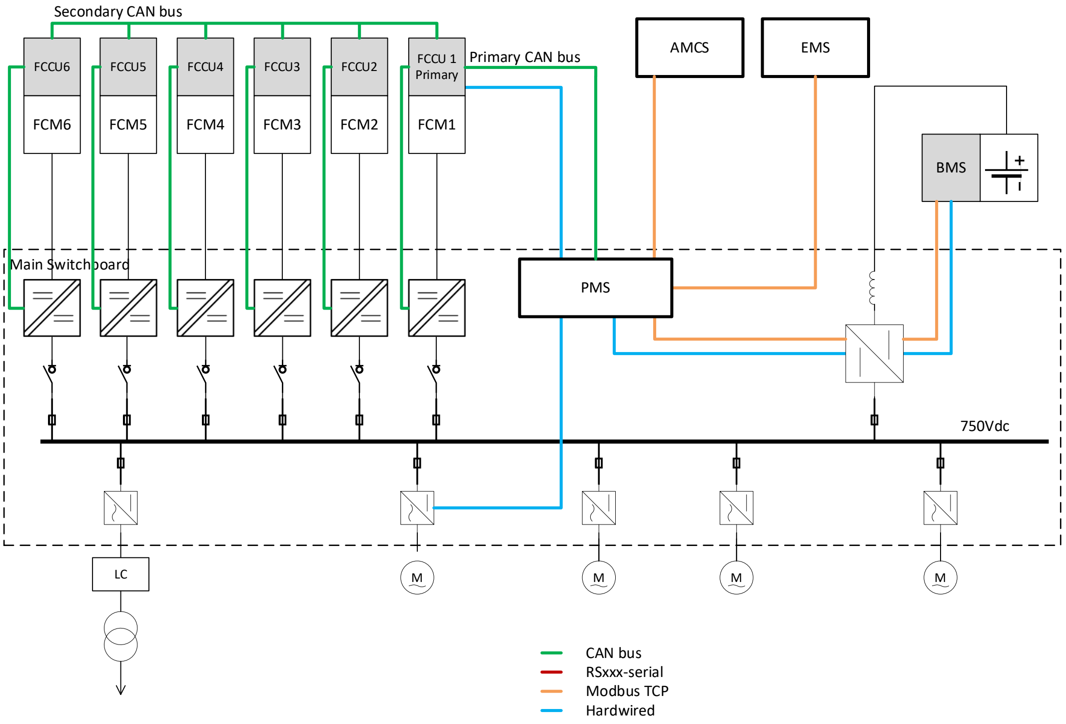

Figure 12 Fuel cell system with non-integrated DC/DC converter on a fixed bus system.

- Connection – The power connection between the FCM and the switch must be made using cables according to marine certification. This is both the constructional requirements (IEC 60009-352) as well as sizing according to classification rules. Standard tables are given by each classification body for various temperatures. For typical XLPE insulated cables, the maximum conductor temperature is to be limited to 90°C.

- Units in parallel – For the power required, e.g. six FCMs are required per side to ensure this power is available at EoL. Each of the incoming feeders to the main switchboard needs to be provided with overcurrent protection (typically aR type fuses in DC application), and an additional isolator switch could be also provided (optional depending on applicable rules) to separate the FCM for disconnection purposes. If the FCM includes overcurrent protection at its output, it may be feasible to combine FCM outputs to common switchboard connections, saving space in the main switchboard. Further implications about parallel operation are given in the control section.

- Voltage and power output – The voltage in a fixed bus system is nominally fixed (with operational tolerances such as droop). In the case of an integrated DC/DC converter it must be ensured that any constraints placed by the power electronics are taken into account (e.g. max/min voltages). In the case of a non-integrated converter, the maximum step-up ratio of the converter needs to be taken into account. Depending on the converter topology, constraints can be placed on the minimum DC bus voltage (e.g. in a buck-boost topology the HV side must always be higher than the LV side).

- Earthing / grounding – for safety purposes, all exposed metallic parts of equipment must be solidly bonded to ground. This is to be provided by means of visible grounding points to ensure that no dangerous touch potentials can arise in case of an internal failure. Maritime DC power systems are typically ungrounded (IT), where none of the system's poles (+ or -) are intentionally connected to ground. This is done for increased availability, such that a first earth fault does not cause a trip of the whole system. For earth fault detection, Insulation Monitoring Devices (IMD) are used which detect when a low resistance to ground is present (unintended connection to earth).

- Isolation – Fuel cell stacks exhibit a low impedance path to ground via the coolant. Deionisation of the coolant addresses this issue but experience in other sectors has shown that this level of conductivity is still not sufficient for isolation levels above 375kΩ[1]. Galvanically isolated DC/DC converters are highly beneficial in such cases especially since adding multiple parallel units will further decrease the effective resistance to earth.

- EMC – Emission limits for components installed in ship applications are specified in IEC 60533. Power systems where the power electronic load dominates are classed as special power distribution zones, where emissions are not restricted, placing instead a requirement on an EMC plan for assessing risks and mitigating measures.

- Black-out start / start-up time and power – In order to start up in case of a blacked out system (no power on main power system) the black out start procedure and system needs to be addressed in the system design. As a minimum, auxiliary power for the control system needs to be provided and the main DC bus energized from a backup power supply (e.g. HV batteries). It is preferred to have the FCM energize the main HV bus with solely the auxiliary control system energized. Logics based on start-up sequence need to be provided at secondary control level (PMS) to ensure correct sequence of loads being started up.

3.3.2 Control

- Control interface – maritime power systems are overall regulated and monitored by a hierarchical Power Management Systems (PMS). This received current operating values and limits from lower level systems, while returning setpoints and commands. Hardwired signals have been traditionally preferred due to perceived robustness and ease of troubleshooting. Fieldbuses are nowadays also commonly used, permitting larger amounts of data exchange with simpler installations. In maritime applications Modbus TCP is a commonly used fieldbus as well as CAN bus (especially in smaller subsystems). Emergency stop signals must always be hardwired.

- Having multiple FCMs in parallel with a regulated converter would require an individual setpoint to be sent to each. This leads to the option of having a PMS field for each FCM or having a single PMS control field and a master FCCU. Having an

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[1] A guidance figure of 500Ω/V is given in DNV-RU-SHIP Pt. 4 Ch. 8 Sec. 3, 4.3.3 for distribution system insulation resistance.

individual PMS field can lead to scalability limitations especially in multi-master PMS types where an individual physical controller is used per field. In case of a master FCCU, a single PMS field manages a number of parallel FCMs by communicating with a single mater FCCU which relays commands and signals to/from the respective units over a secondary bus.

- Power control – Parallel sources typically controlled by using regulated voltage droop (in case of DC systems). Voltage setpoints are issued to each controlled source to implicitly regulate to the power as requested by the PMS. The FCMs require a power/current setpoint, and therefore rely on other sources to take up power fluctuations. The PMS must therefore periodically update the reference power setpoint within the allowed FCM power ramp limits. Any minimum power limits from the FCM would also need to be respected and implemented by the PMS as a minimum setpoint. At a design stage this would need to be taken into account in sizing of the FCM and battery to ensure there is enough capacity for a minimum FCM load.

3.4 External safety systems

In order to mitigate possible dangerous situations external safety systems are required. The safety systems are often connected to the FCM in order to initiate an Emergency Shut Down (ESD). If the concentration of hydrogen has increased up to 25% of the lower explosive limit of hydrogen, the system should shut off automatically. Therefore, sensors have to be placed on locations where one would expect an accumulation of hydrogen. Also, the FCM is de-energized and the hydrogen supply blocked. This should prevent accumulation of hydrogen and the FCM acting as possible ignition source. Typical triggers are hydrogen detection or accident detection for road application.

In case of an emergency shutdown, the maritime application requires redundancy to prevent a total blackout of the ship. A second system in parallel or batteries as a backup can be used. For the maritime and certain road applications it is also required to detect fires and have a fixed fire fighting system. So in case of fire, the situation can be mitigated. This requires a specific fire fighting system that is able to extinguish a hydrogen fire and should be able to detect it.

For the marine application, also passive measures are required, like A60 fire insulation on the FCM enclosed space. Also fire dampers for ventilation inlet and outlets are part of the safety measures.

4 Process flow diagram

This chapter presents two examples of process flow diagrams for various applications. This is basically a condensed summary of chapter 3 for the hydraulic and pneumatic connections.

The first process flow diagram is applied for most applications with natural ventilation, see Figure 13. Emergency shutdown is the applied safety concept. All the components and connections are installed in open air. This makes it a very straightforward solution. Since it is outside, it is less dangerous if hydrogen leaks since it will immediately rise and dilute. The only hydrogen detection is installed within the FCM and when detection occurs the hydrogen supply will be blocked.

This concepts makes it also quite straightforward to interconnect multiple FCM for scale up of power. Most of the connections will be made in parallel and interconnections can be applied if this is beneficial.

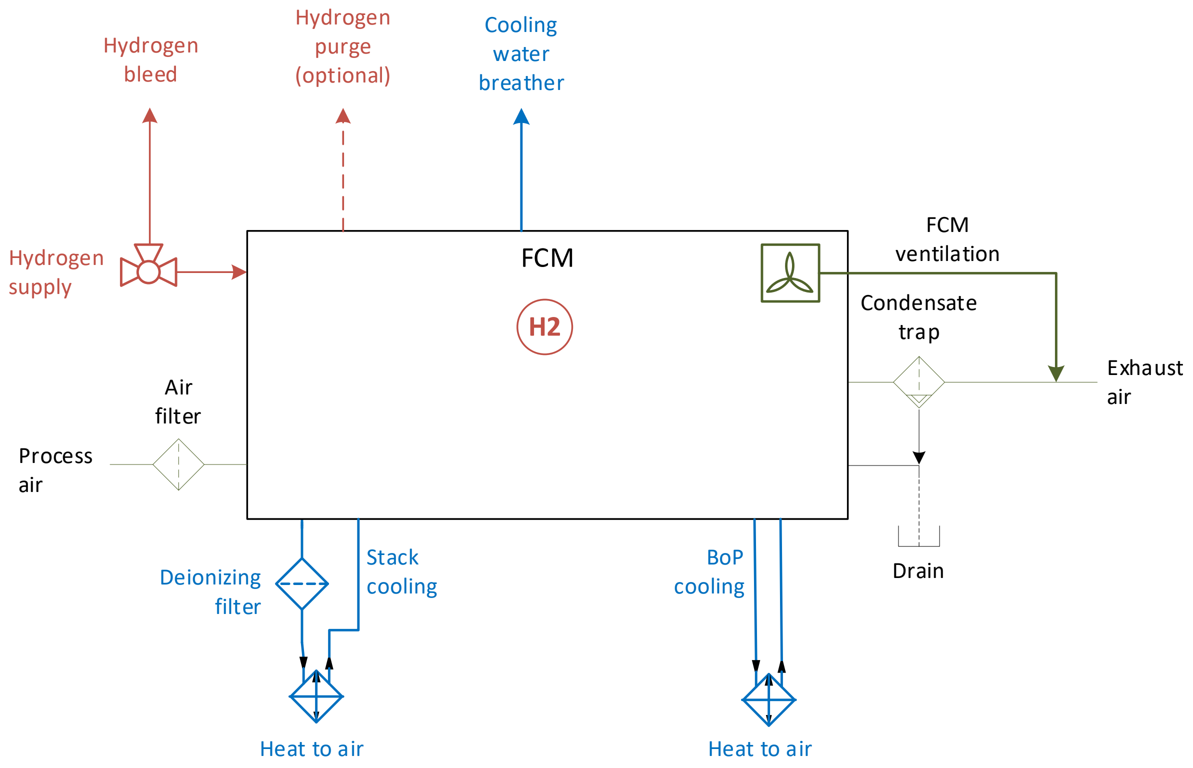

Figure 13: Basic diagram for natural ventilated FCM with ESD protection

The second process flow diagram is mostly applied for the maritime application and is based on enclosed installation with double barrier protection, see Figure 14. This means each potential hydrogen leak will flow towards a safe area. This safe area has no ignition sources, so ATEX equipment might be required. Also, the level of detection and redundancy is increased. Hydrogen detection is required in the FCM ventilation, cooling water breather and enclosed space. The FCM ventilation has to be redundant with a full back-up and monitored on proper functioning. Overall, the increased level of safety makes the installation more complex.

This concepts makes it way harder to scale-up power by combining multiple FCM. All the separate connections and hydrogen detection results in many piping which makes it rather chaotic. It seems to make more sense to install a few larger FCM's than multiple smaller FCM's. More development seems required to shift the balance for this application.

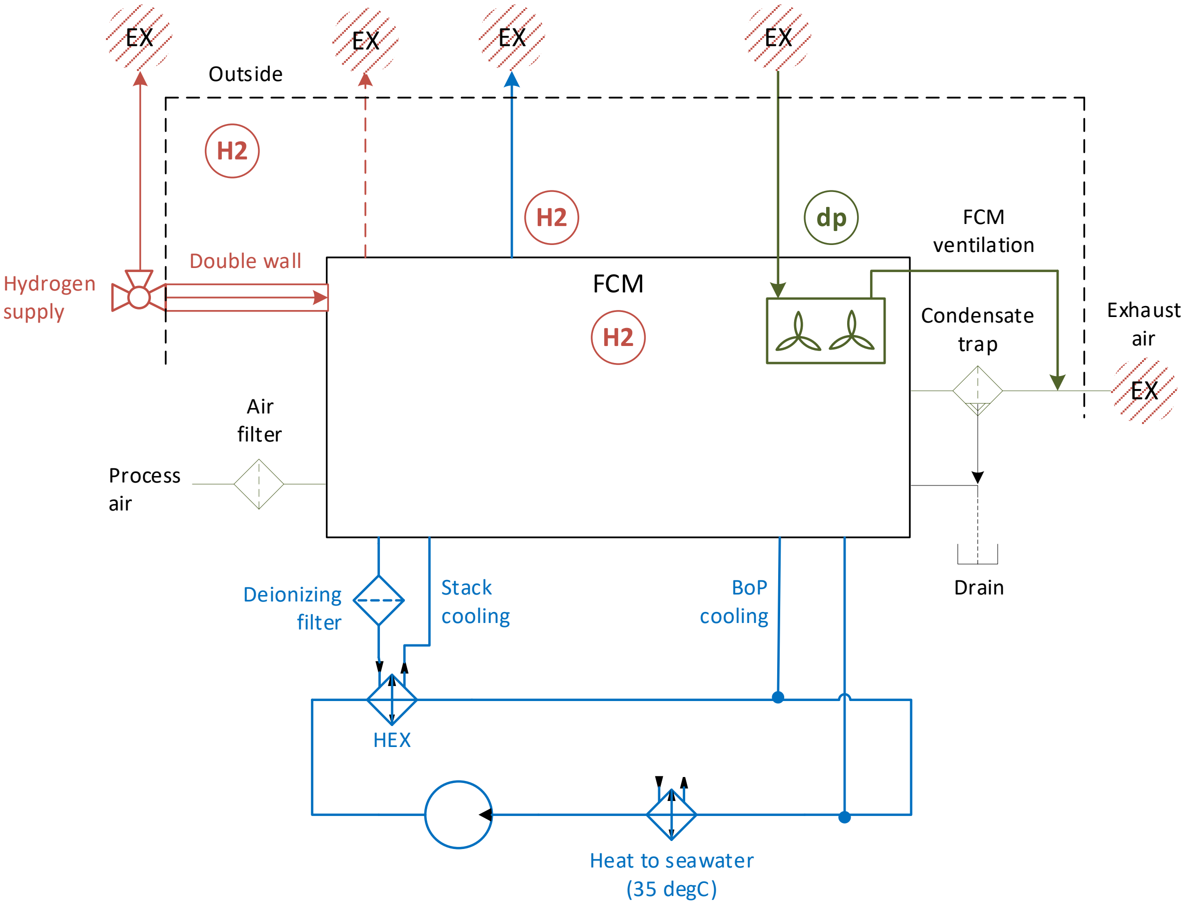

Figure 14: Basic diagram for enclosed FCM installation with double barrier protection (gas-safe space)

5 Conclusion & recommendations

5.1 Conclusion

This report elaborates on the application of the StasHH standard interface FCM for the various applications. As it seems for most applications the standard interface works out and is able to scale with multiple FCM's. Some FCM have already been used successfully in practise. These tend to be mostly natural ventilated installations with emergency shutdown protection.

From a functional point of view the StasHH standard will suit every application. In terms of reliability, durability and lifetime, requirements are quite in line.

From a safety point of view, the maritime application or enclosed installation with double barrier protection, seems to be harder to install the FCM successfully. At this moment in time there are gaps between the standard interface and the recently published guidelines from [IMO] and [Lloyds]. The double barrier protection approach gives more demanding safety features which are not incorporated in the StasHH standard interface. The StasHH standard is a combination between safety concept A and B from Figure 10. This makes it difficult to assess, because it does not fully comply to one of these concepts. Additionally, a final risk assessment is required to get a final conclusion, but gives also freedom to deviate from the full prescribed safety concepts. More specifically, the following interfaces / subsystems give doubts:

- Double walled hydrogen supply connection: This is a benefit in terms of fuel cell space ventilation. It is unclear from [IMO] and [Lloyds] which leakage scenario needs to be considered for a single walled pipe. Therefore the ventilation rate can not be determined. The ventilation rate for a full pipe rupture with maximum 25% LEL seems very hard to achieve.
- FCM ventilation concept: The FCM are gastight, but the FCM ventilation system is not according to maritime standards. This might give complications for safety concept A and B. A, because the natural ventilation is too low. B, because redundancy is too low.
- Purging: A (nitrogen) purging system might be required to reduces risks after ESD or in case of maintenance.

5.2 Recommendations

From the available documentation from the FC suppliers only installation details of a single FCM could be derived. It is recommended that also the installation of multiple FCM would be described. Clarification is required in terms of series connection for the hydraulic and pneumatic connections. Also, master / slave control for the automation systems could be considered.

Current prescriptive guidelines for the maritime application do not fully comply with the StasHH standard. It is recommended for the FCM suppliers to study these documents. With a proper motivation it is possible to influence regulation. Otherwise, changes towards the design can be considered.

References

[IMO]	International Maritime Organisation, MSC.1/Circ.1647, Interim guidelines for the safety of ships using fuel cell power installations, 15 June 2022
[Lloyds]	Lloyd's Register Group Limited, Guidance Notes on the Installation of Fuel Cells on Ships, April 2023

Appendix 1: Physical arrangement detailed table

	Off-road	**Rail**	**Road**	**Stationary**	**Water**
Location	Outside	Roof or inside car body shell	Outside	Inside	Inside
IP rating	IP67 Water from wheels	Depend on equipment's, as per EN 60529	IP67 Water from wheels	IP67	Low (IP22)
Ventilation	Natural	Natural	Natural	Semi enclosed, Not vented	Forced, under pressure
Hazardous area	N.A. only inside buildings during maintenance		N.A. only inside buildings during maintenance	N.A.	Yes IMO MSC.1/Circ. 1647
Orientation	Horizontal	Depend on train location as mentioned	Replace tank or engine, horizontal	Straight	Straight / flat
Inclination	30 deg up to 45 deg as extreme for short periods	- 4% in slope in the longitudinal directions (2.3°) - 7.2° in transversal directions	30 deg	Only during transport	IACS UR E10
Acceleration					IACS UR E10
Vibration	Hydraulic equipment N.A.	Category 1 Class A of IEC61373-2010	? (Road certified)		IACS UR E10 (Resilient mounts?)
Shock	N.A. Resilient mounts	Category 1 Class A of IEC61373-2010	Potholes (Road certified)		

Appendix 2: Cooling water circuit details

	Off-road	**Rail**	**Road**	**Stationary**	**Water**
Liquid type		DI water + Glycol	DI-water		1st loop DI water; 2nd loop glycol
Temperatures	Min. -20 deg C outside air Max. 45 deg C outside air				Min. -10 deg C Max. 35 deg C seawater
Hydrogen escape	N.A.				
De-ionizing filters	Yes				
Direct or indirect cooling	Direct cooling				Indirect: FCR HEX1 and external HEX2. External can be open or closed.
HEX type	Forced air cooling	Forced air cooling	Separate coolers, liquid/air Soldering with vacuum because DI water.		Liquid to liquid
Start-up		Using battery energy	Small heaters and by-pass loop to start		Using battery energy

Appendix 3: Air intake, exhaust & ventilation

	Off-road	Rail	Road	Stationary	Water
Ambient conditions		0 to 1600m			
Air quality					
Filter / inlet requirements			External exhaust gasses		Salinity
Hazardous areas					Yes IMO MSC.1/Circ. 1647
FCM ventilation	Yes, should stay below LEL in each condition				
External influences		Tunnels, crossing trains	Garage Workshop Ferry		Bridges, locks.

Appendix 4: Hydrogen supply

	Off-road	Rail	Road	Stationary	Water
Supply pressure					Influences the FCR ventilation rate, IMO MSC.1/Circ. 1647
Temperature					Cylinder on roof, could get cold and hot?!
Hydrogen quality		EN17124 and/or IEC14687			ISO 14687 or SAE J2719
Return flow					Not preferred
Purge for start-up or shut down / Gas freeing					Passive system preferred
Connection type					

Appendix 5: Electrical

	Off-road	Rail	Road	Stationary	Water
Connection / HV interlock		Inside box	Inside box		Compliant cable sizes
Units in parallel		Depend on application (Commuter, Regional, Locomotive)	4 in parallel	5	Must! Droop control preferred
Voltage and power output			Same as battery voltage		<800V & <1000Vdc 1300V?
Earthing / grounding					
Isolation			500Ohm/V		Isolation necessary?
EMC		EN 50121-3-2:2015	Homologisation required		In special power distribution zone
Black-out start / start-up time and power		DC bus energized	DC bus energized		HV bus energization sufficient? Minimum SoC required 24V

Appendix 6: Control

	Off-road	Rail	Road	Stationary	Water
State control			Follows D3.4		Commands from PMS over CAN bus. How to handle multiple units?
Power control		CAN or Modbus TCP			Power setpoint to FCCU over CAN bus.
Auxiliary control			Handled in state machine		Auxiliaries handled internally. How about startup procedure?

Appendix 7: Safety systems

	Off-road	**Rail**	**Road**	**Stationary**	**Water**
Purge system	N.A.				
Hydrogen detection			Exhaust		Fuel cell room Pneumatic connections Cooling water
Emergency shutdown	H2 leak HW e-Stop				
Instantly de-energized	Yes				
Fire detection		Line Heat Detector			IR camera
Firefighting system	None				Foam
Accident detection		None			N.A.
Fire & Smoke (Rail)		EN 45545-2			