Fuel Cell Solution for Marine Applications

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Abstract

With future regulations on the horizon, port authorities and ship owners/operators are looking at alternative propulsion solutions to reduce emission. Fuel cell technology provides an attractive zero-emission solution to generate electric power on board using hydrogen as a fuel. Fuel cell systems are scalable from 200kW to multi-MW providing high efficiency, dispatchable, clean quiet power generation. Several innovative pilot projects are on the way to demonstrate the marine application of this proven technology. Electrification of propulsion systems is advancing, and fuel cell technology provides the opportunity to produce, on board, large quantity of power with zero-emission using hydrogen as a fuel. We will present the value proposition of having a fuel cell power generator on board of an electric vessel while discussing the safety considerations with the fuel cell module and the on-board fuel storage. We will present some of our current fuel cell marine projects and review some of the product development considerations including, system architecture and safety as well as hydrogen supply and on-board fuel storage.

1. About Ballard

Ballard Power Systems Europe A/S, Hobro, Denmark is the European head quarter of Canadian Ballard Power Systems Inc. Ballard's zero-emission PEM fuel cell solutions bring compelling value propositions to end users' markets such as backup power and enable electrification of mobility, including marine vessels, buses, commercial trucks, trains and forklift trucks. We are working to accelerate fuel cell technology adoption, committed to provide fuel cell power for a sustainable planet.

2. Executive Summary

Strict emission targets are being set by the shipping industry with the target of going to zero-emission on Norwegian fjords by 2026, the IMO cutting GHG emissions by 2050 and EMSA cutting CO_2 emissions by 50% by 2050. Like all heavy duty transport applications, shipping currently only has two options for zero-emission transport, battery electric or hydrogen fuel cell electric. A hydrogen fuel cell has advantages over battery electric because of its:

- Longer range
- Shorter fuelling times
- Scalability and modularity
- Stable, reliable power

Introducing hydrogen as a fuel for sea going ships presents different possible hazards that has to be mitigated, particularly as any assistance could be many hours away in case of an accident. This paper considers the safety implications in the design of a fuel cell module for marine applications.

From the very start of the design concept, safety must be a priority consideration, built into the energy providing fuel cell module. Thus, safety engineering has to be at the heart of the development process of a marine hydrogen fuel cell and hydrogen fuelling system. Within this, there has to be an identification of potential hazards. Using safety related design principles, any risks have to be eliminated in the design phase. Today, there are not many relevant hydrogen regulations, codes and standards (RCS) available as these often follow development of new innovative designs. RCS from other fuels and technologies can be used as reference with close characteristics similar to hydrogen or RCS from related industries that have already started using heavy duty fuel cell solutions.

Safety systems can be built into the design to ensure that an early warning is given if things are not working correctly. Care must be taken to ensure that calibration is kept up to date to the manufacturer's instructions so that false alarms are not given.

During the design phase, close cooperation should be used with regulatory authorities to ensure the product created is able to be approved.

Ballard are taking part in a number of projects that showcase fuel cell powered propulsion in marine vessels. Our marine fuel cell projects include Flagships, HFC Marine, ShippingLab and HySEAS III.

3. Contents

4. Introduction

With future regulations on the horizon, port authorities and ship owners/operators are looking at alternative propulsion to reduce emissions. Fuel cell technology provides an attractive zero-emission solution to generate electric power on board using hydrogen as a fuel and are widely considered as one of the most promising solutions for reducing harmful pollutants.

Ballard fuel cell systems for marine use are scalable from 200kW to multi-MW providing high efficiency, dispatchable, clean quiet power generation. Several innovative pilot projects are on the way to demonstrate the marine application of this proven technology.

Electrification of propulsion systems is advancing, and fuel cell technology provides the opportunity to produce, on board, large quantity of zero-emission power using hydrogen as a fuel.

In the following, we will present the value proposition of having a fuel cell power generator on board of an electric vessel while discussing the safety considerations with the fuel cell module design and the on-board fuel storage.

5. Moving to zero-emission

On a global scale the shipping industry contributes a significant share of greenhouse gas emissions (GHG), 2.2% of CO_2 15% of NOx and 13% of SOx per year. With world trade increasing this pollution will continue to rise if nothing is done to reduce the dependence on fossil fuels.[1]

Organizations and governments are taking action to tighten GHG emission standards for vessels, and zero-emission requirements are being implemented into the marine industry.

- The International Maritime Organisation (IMO) is looking to phase out GHG emissions and has set a target of a 50% reduction by 2050. [1]
- Norway is protecting its fjords by requiring shipping to be 100% zero-emission by 2026. [2]
- Europe European Maritime Safety Agency (EMSA) is to cut CO_2 by 50% by 2050. [3]

Hence, with the requirement for GHG reductions in the marine industry, the need for zero-emission technologies is growing.

6. Hydrogen and Fuel Cells

Fuel cells are widely considered as one of the most promising solutions for reducing harmful pollutants and will play a key role in helping the marine industry address GHG emissions on the water, and in ports. As with all heavy-duty transport, currently there are only two options for operating zero-emission vessels, battery electric or hydrogen fuel cell.

A fuel cell vessel is powered by a hybrid electric system that includes both fuel cells and batteries working seamlessly together to provide efficient zero-emission power. Hybrid systems are designed so the fuel cells operate at steady state and the batteries are sized for transient power requirements.
Just like batteries, fuel cells produce electricity with high efficiency through an electro-chemical process. The difference is, with fuel cells, energy is stored separately in the form of hydrogen fuel. As long as fuel is available, the fuel cell modules will produce electricity and the only emissions from fuel cells are water, water vapor and heat.

[1] The % of emissions will also rise as other sectors reduce their share of GHG emissions.

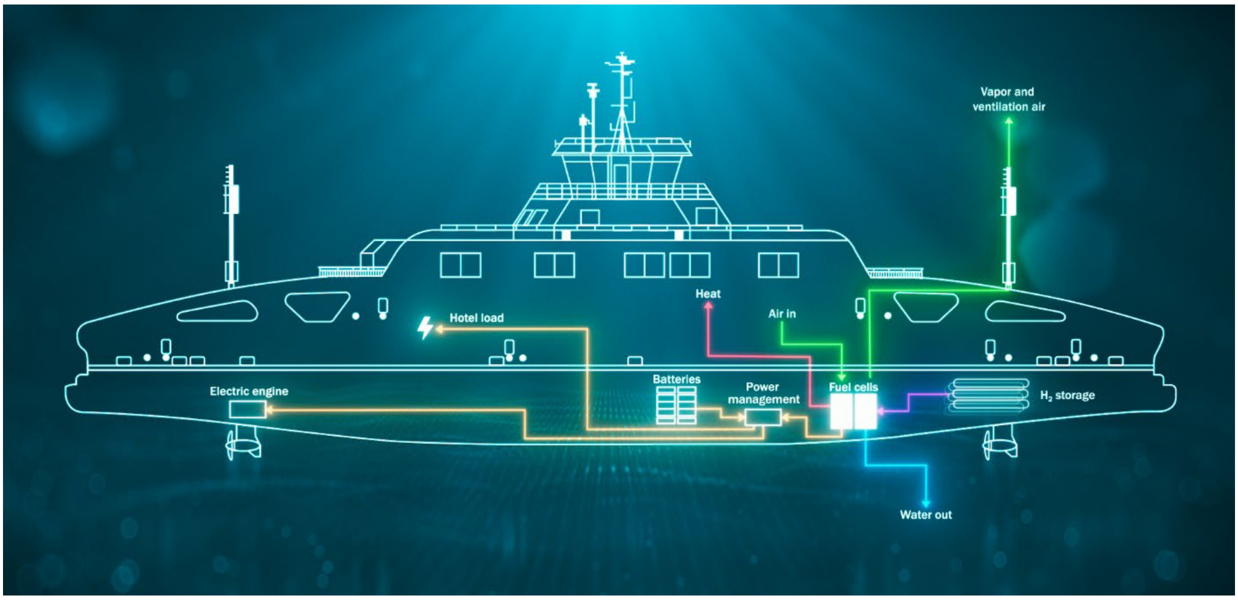

Figure 1

Hydrogen fuel cells offer the following advantages over battery electric in the marine environment:

- **Longer range**
  - Fuel cell powered vessels can run longer and travel farther before refuelling when compared with the other zero-emission option of a battery powered vessel.
- **Fuelling speed**
  - Fast liquid refuelling can take place with no long recharging intervals as there would be with a battery electric powered version.
- **Scalability and modularity**
  - Fuel cell modules can give flexible configurations that can adapt to vessel space constraints. Deployed in parallel, fuel cell modules have dispatchable configurations to meet variable power requirements.
- **Stable, reliable power**
  - Hydrogen fuel cell modules require very little maintenance, have low maintenance costs and an extremely long service life.

7. Safety Engineering as Part of the Development Process

Safety, as in all hydrogen projects, is something that has to be considered from the start of the development process, and this is no different when looking at a marine project. Because of the nature of operation of the marine sector vessels are often alone at sea and have to deal with issues remotely, including safety related events. They can be without outside assistance for many hours. It is, therefore, vital that safety is taking into consideration and designed in to a marine project from the beginning.

7.1 Regulations, Codes and Standards (RCS)

Any new design has to adhere to current regulations, codes and standards (RCS), however often during innovations these can be immature. If there are not directly applicable RCS, then good practice is to use RCS currently available. In the case of hydrogen systems, an example could be compressed natural gas standards (CNG) and abide as much as possible by them. Examples of RCS for consideration for the hydrogen system design process are shown in Table 1.

Table 1

RCS	Title	Brief Description
IEC62282	Recommended Practice for General Fuel Cell Vehicle Safety	This gives guidance, good practice and safety requirements for fuel cell vehicles.
IGF Code	International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels	This is a mandatory safety code from the International Maritime Organization (IMO) for ships using gases or other low-flashpoint fuels. The code includes mandatory criteria for the arrangement and installation of machinery to minimise the risk to the ship, its crew, and the environment.
IEC60079-10	Explosive atmospheres – Part 10-1: Classification of areas – Explosive gas atmospheres	This standard is concerned with the classification of areas where flammable gas of vapours may occur. From this classification the basis to support design, construction and operation of equipment that is to be used in this hazardous area.
IEC60079-14	Electrical apparatus for explosive gas atmospheres – Part 14: Electrical installations in hazardous areas (other than mines)	This part of the IEC 60079 has specific requirements for the design, selection, erection and initial inspection of electric installation in, or associated with, explosive atmospheres.
IEC60092-504	Electrical Installations in Ships, Automation, Control and instrumentation	This standard specifies electrical, electronic and programmable equipment intended for automation, control, monitoring, alert and safety protections systems used in ships.
DNV-GL Rules Part 6, Chapter 2, Section 3	Fuel Cell Installations	To ensure that fuel cell power installations can be operated safely and with a defined degree of availability, the objective of this section of the DNV-GL Rules is to provide the requirements to ensure this. The standard covers all aspects of the installation form from the installation of the primary fuel supply, including reformers used to convert liquid or gaseous primary fuels to reformed hydrogen rich gas, up to the exhaust gas system.

7.2 Identification of Potential Hazards

Early in the design process it is essential to assess the potential hazards that a hydrogen fuel cell marine operation may incur. There are a number of routes to identifying these potential hazards. First, multidisciplinary workshops should be set up to discuss hazards that could occur. By drawing on the experience of individuals from both within and outside the organisation, potential hazards can be foreseen. It is likely that the developer of the product may not have a vast knowledge of the industry that the product is going to be entering. This process must however not bow to preconceptions of hydrogen and every point raised must be analysed and assessed so an appropriate understanding of the hazards can be gained.

An operational understanding and an analysis of potential misuse and failures of the hydrogen fuel cell systems is the second issue that is dealt with in the identification of potential hazards. The understanding of any potential misuse can mean that this can be designed out so this misuse cannot take place in the future. Failures and failure analysis can lead to an understanding of where things can go wrong. Again, if an item is expected to fail then it can be replaced with a new design at this phase, or if it is a component that may have to be changed in the future, then design can be made to ensure that the maintenance can be carried out in such a method that safety is not compromised.

Figure 2

Finally, Ballard has over 40 years' experience in the design and implementation of fuel cells in heavy duty transport. Hydrogen fuel cells have proven their performance in a variety of applications including buses, trucks, cars, forklifts, and passenger trains. Now, fuel cells are also being integrated into vessels, and Ballard possess a grand experience, that can be drawn upon to ensure that issues that have occurred in the past are not repeated in to the marine product.

Ballard's FCwave^{TM} module for marine applications, was designed hand-in-hand with the marine industry to withstand the rigors of the marine environment and to be able to meet stringent safety standards. Thus, it as a clear advantage to be aligned with the expectations of the industry and learn from their experience. Ship yards for example have vast experience as they are normally older established companies and can offer specifics from the marine industry into the development and design process.

7.3 Safe Design Principles

Once risks have been identified in the system, the task is to eliminate those risks from the hydrogen fuel cell module and the hydrogen system generally. This can be as simple as changing a specific component or it can be a redesign of a certain element of the system. Redesigns can be costly, so the earlier the hazards and associated risks are identified in the design process, the cost of rectification is less and often simpler.

There may not be specific regulations, codes and standards (RCS) for the sector that you are designing for, this is true in the marine environment where fuel cells and hydrogen have not previously been used for the vessel propulsion. Often RCS follow innovation by about three years. There may be some relevant general RCS that apply or there could be some RCS that are applicable to similar forms of fuel storage or propulsion system that could give a base level of what is required. Good practice can also be looked at from a similar fuel storage or propulsion system.

RCS from other fields, in this instance using heavy duty fuel cell systems, can be imported in to the design to give a basis on the good practice going forward.

7.4 Instrumentation and Safety Systems

Even with identification of potential hazards and implementing safe design principles there will still be items that have not been considered, or as part of the risk profile from the identification of potential hazards could not be completely eliminated. So, to ensure safe operation of the hydrogen fuel cell module there are requirements to implement instrumentation and monitoring to ensure that if something does go wrong, there is an early warning that can stop an incident escalating.

The first, and probably protecting the most catastrophic event are sensors for monitoring hydrogen gas concentrations outside of where hydrogen is expected to be. A hydrogen leak, although unlikely, is possible so an early warning system alongside mitigation measures and procedures can reduce the likelihood of a leak causing a larger issue.

Fire detection is also an important mitigation that can give an early warning and enable a safe shut down of systems to stop a fire escalating to a major incident.

Other control and monitoring systems must be incorporated in to the design to ensure that there is the safe operation of the fuel cell module. Controlling and monitoring systems should be independent so that there is not a chance of a failure in the main system to cause the monitoring to also fail at the same time.

As with all monitoring systems, it is important that they are correctly maintained and calibrated to the manufacturer's schedule to ensure that they do the task of providing safe monitoring of equipment correctly. Multiple false alarms can lead to not trusting a safety system and potentially ignoring it when in fact there is a real incident.

7.5 Product Approval

Through the design and the development, it is important to have the approval classification bodies involved to ensure the that the design concept, and subsequently the design, will meet the level required for marine use certification.

Documentation is key to certification bodies, the early adoption of producing the documentation of the safety concept will give re-assurance in the design process that subjects are being covered.

By seeking early dialogue with certification bodies, it ensures that there is an acceleration of the classification process at the end of the project.

8. Hydrogen Storage Systems for Marine Applications

The larger the vessel the greater the fuel volume requirement is for a maritime vessel. Both the distance and time between fuelling opportunities can be large. There are three methods that today are used to provide hydrogen to the fuel cell system. Wherever there is hydrogen storage there has to be some consideration for ventilation so that any leaks of hydrogen can be removed out of the enclosed space of the vessel into the atmosphere.

8.1 Compressed Hydrogen Storage

Compressed hydrogen storage is the main method of hydrogen storage on heavy duty vehicles. This is normally at 35MPa on heavy duty vehicles such as buses and trucks. On passenger vehicles the normal compressed hydrogen is at 70MPa. On vessels, the 35MPa or 50MPa storage methods are used on the first trials, mainly because components for this method are commercially available. Normally on a heavy duty vehicle the pressure cylinder is either Type 3 or now moving to Type 4. The same gaseous pressure storage can be used in the marine environment, normally in a containerised form. This would hold approximately 1000kg for a 40ft (12m) container size. This would be about 0.5MWh$_e$/m^3 with PEM fuel cell systems.

Safety considerations are around a leak where potentially at this pressure it could develop into a jet flame.

8.2 Liquid Hydrogen Storage

With a storage capacity of approximately 1 MWh$_e$/m^3 with fuel cell systems, liquid hydrogen is better for high capacity storage on vessels. The output pressure of such a system would be 150 kPa-800kPa. Measures would have to be undertaken to safely turn the liquid hydrogen into gaseous hydrogen for delivery into the fuel cell module. There are some concerns with liquid hydrogen storage if there is a spillage that would have to be considered for an onboard application. Liquid hydrogen is a cryogenic system, where the hydrogen is stored at -253ºC. If there is a spillage of this hydrogen, there could be serious consequences if it comes in to contact with a person causing serious cryogenic burns. Also, there would be a rapid evaporation and expansion causing pressure issues so it would have to be ensured that there was adequate venting in the room to cope with this spillage. The effect of the cryogenic hydrogen on a steel surface could be severe as there is a decrease in toughness as the temperature decreases.[4]

A fuelling solution for cryogenic hydrogen would have to be developed that ensures that there is no leakage during the fuelling process.

One of the issues is that there can be boil off or the hydrogen warming slightly causing evaporation so rapid expansion in the sealed hydrogen system. Although the storage vessel must be designed so that the hydrogen does not suffer from boil off, measures must be put in place to ensure that if this happens, either in the fuelling system, the pipework or in the storage tank there are adequate venting measures that will stop a build-up of pressure potentially causing a pipe or tank fracture. This may include a regular maintenance of venting off the gaseous hydrogen.

8.3 Onboard Hydrogen Production

On large vessels, the energy carrier could be different from hydrogen such as methanol or liquid natural gas (LNG). The fuel cell could have an integrated reformer that can separate out the hydrogen to be used in the fuel cell. This process would produce local CO_2 emissions, but this could be neutralised using bio or renewable fuel.

Methanol and LNG storage are already used in other applications and so their storage and transportation are already well known. This could make the operator more comfortable about using these fuels rather than pure hydrogen storage. There are also transportation routes with methanol and LNG that are already established. The problem with this solution is that it adds a new level of complexity in to the system that is on board the ship.

9. Possible Required Fundamental Research.

There is a lot of research, information and understanding on gaseous leaks of pressurised hydrogen. The hazard that pressurised gaseous hydrogen can create, in the worst circumstances leading to a jet flame or accumulation of a hydrogen cloud to form a detonation or deflagration can be mitigated against.

It is possible that liquid hydrogen fuel storage may be used on a vessel. The result of a large liquid hydrogen spillage is less known and the consequences of this in an enclosed space or if the liquid hydrogen spilt on to water.

More investigation in to liquid hydrogen spillages could be an asset to marine fuel cells and the understanding of the use of hydrogen and hydrogen fuel cells in the decarbonisation of the marine industry.

10. Marine Projects Powered by Ballard Fuel Cell Modules

Europe has a strong history of maritime and shipbuilding leadership and is focused on maintaining this position as the market transitions to zero-emission. European projects and funding reflect this focus and, currently, the European zero-emission marine market is more advanced than other regions. Ballard is engaged in several projects in Europe, briefly described below. Together with our growing industry partnerships, these projects are helping guide Ballard's fuel cell strategy for the marine sector. And we use our fuel cell expertise to deliver reliable, valuable, and innovative solutions to our Marine customers enabling them to meet requirements for zero-emission marine propulsion.

10.1 Flagships

Figure 3

The FLAGSHIPS project raises the readiness of zero-emission waterborne transport to a new level by demonstrating two commercially operated hydrogen fuel cell vessels. The vessels will be operating in France (Lyon) and in Norway (Stavanger). The Lyon vessel is a push-boat operating as a utility vessel on one of the most demanding rivers, the Rhône, while the Stavanger project is a passenger ferry operating as part of the local public transport network. In the project, a total of 1MW (400kW + 600kW) of on-board fuel cell power will be installed. Gaseous (Lyon) and liquid (Stavanger) hydrogen will be used on-board these vessels.

This project indicates a 200kW building block is appropriate for smaller vessels. The project also assists to prepare Ballard's heavy duty fuel cell modules for maritime applications. Collaboration with industry partners is important for improving integration into the vessel propulsion system.

Safety is a key issue when developing hydrogen fuel cell products, and maritime fuel cell products are no exception. Safety meetings have taken place on both the Lyon projects and the Stavanger project. Hazard identification (HAZID) workshops have taken place for both vessels, particularly surrounding the storing and bunkering of hydrogen. [5]

10.2 HFC Marine

This project addresses the development of hybrid electrical propulsion of ships where the electrical power is partly supplied from batteries and partly generated on-board by means of fuel cells fuelled by hydrogen. The fuel cell technology will allow for faster refuelling and longer distance between refuelling compared to ships with only batteries. The hybrid combination of batteries and fuel cells will deliver efficient and reliable supply of electricity for propulsion. The project is a first step (phase 1) for applying a hybrid battery and fuel cells solution to ships. The project will be followed by a demonstration project (phase 2).
The project will help to guide the power specification of fuel cell module building blocks and will help to understand fuel cell module performance in hybrid marine applications.

Several sub-systems and interfaces need to be addressed to integrate hydrogen fuel cell technology on a ship, including the safety systems and alarms on hydrogen solutions on board.

10.3 ShippingLab

The ShippingLab project is a part of the Danish and worldwide merchant fleets transition towards greener shipping. The core elements in the project are Autonomous shipping , Digitalization and Decarbonization the project is scoped between strong partners such as several ship owners, green technology industry companies, research institutions, a maritime industry organization and a maritime cluster. Overall, the project addresses a key requirement for the future ship and looks into data standards and sharing of digital twin models, operational models for definition of test cycles as well as fuel reduction needed for the decarbonization agenda. Technology for the future autonomous and CO2-neutral ship is developed and demonstrated in a live environment. [6]

10.4 HySEAS III

The HySEAS III project is intended to provide unarguable proof that hydrogen energy can be transferred safely and efficiently to sea-going vessels. HySeas III has the commitment from Transport Scotland (agency of the Scottish Government) that such proof will lead immediately to the commissioning, development, construction and validation of the world's first zero-emission ferry, powered by hydrogen from local renewable energy sources (wind and tidal energy). It is intended that the concept is commercially viable. With that in mind, the second key objective is the development of a holistic business model for replication in the vast coastal/island regions of Europe, facilitating the roll-out of the zero-emission ferry with landside infrastructure to provide the hydrogen and realization of the associated economic and environmental benefits.

Ballard will participate in the safety-approval of the fuel cell solution and will work on integration with vessel architects and ship builders. We will also provide fuel cell modules of 600kW for the ferry and develop operational lifecycle procedures.

A HAZID workshop has taken place in the project, that was split up in to three sections, the battery set up, the fuel cell and the hydrogen itself storage solution. [7]

10. Marine Centre of Excellence

In 2019 Ballard established the Marine Centre of Excellence in Hobro, Denmark where the fuel cell module FCwave™ is designed and built. The Centre is dedicated to the engineering, manufacturing and service of heavy-duty fuel cell modules specifically for the marine industry and has an annual production capacity of more than 40 MW of fuel cell modules. We collaborate closely with the marine industry to deliver solutions that maximize the full potential of vessels and enable a safe, efficient and sustainable maritime industry.

Figure 4

11. Conclusion

Hydrogen fuel cells are a practical approach towards zero-emission marine operations. Projects already underway are proving the viability and safety of the product. During the design phase of a fuel cell product safety considerations have to be designed in to ensure that there can be approval for the product.

Safety considerations may have to come from a number of sources to ensure that all aspects of the marine operation are taken into account. This also include the hydrogen storage mechanism as there could be a large amount of hydrogen fuel on board.

By taking part in demonstration projects, the viability of fuel cells as a zero-emission propulsion on a marine vessel is being proved.

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