March 2019

INFORMATIONAL

Fuel Cell Applications for Marine Vessels

Why Fuel Cells Make Sense

CONTENTS

INTRODUCTION

Emissions from combusting fossil fuels are damaging to both human health and the environment and efforts are focused on reducing emissions to acceptable levels. In the marine industry, ships powered by diesel and natural gas fuels emit air pollutants while underway on rivers, in littoral waters and open seas, and while powered in port. And the regulations governing these emissions can be different from port, to littorals, to open seas.

Jurisdictions promulgating emission regulations include the IMO (International Maritime Organization), nations, states and provinces, and local governments including port organizations.

IMO INTERNATIONAL MARITIME ORGANIZATION

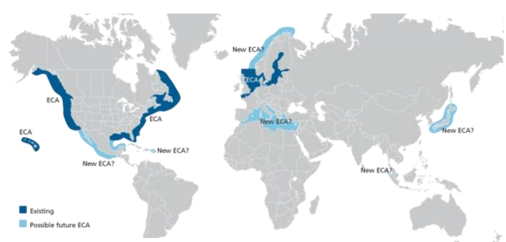
The International Maritime Organization has adopted regulations to address the emission of pollutants from ships and has adopted mandatory energy-efficiency measures to reduce emissions of greenhouse gases (GHGs) from international shipping and finally phase them out as soon as possible in this century. The initial IMO strategy targets a reduction in total GHG emissions from international shipping by at least 50% by 2050 compared to 2008.

In 2015, the Norwegian Parliament adopted the decision, “The Government is requested by the Parliament, to ensure that requirements for zero-emission technology (and low-emission technology) are included in all future tenders for public ferries, when the technology allows for it.”

In Europe, the EMSA (European Maritime Safety Organization) has an objective to cut the EU's carbon dioxide emissions from maritime transport by at least 40% (50% desired) of 2005 levels by 2050. The Norwegian parliament has decreed that the country’s UNESCO-protected fjords shall be free from cruise and ferry emissions no later than 2026.

Alaska has long-established Marine Visible Emission Standards in force. And there is a growing call to protect the sensitive arctic/polar regions from possible spills of marine fuels and emissions from vessels.

Emission Control Areas (ECAs) have been adopted by the IMO for North America including the Hawaiian Islands, and the Baltic and North Seas. Currently, NOx SOx, and particulate matter are controlled within these areas. ECAs are discussed for the arctic, Central America, the Mediterranean and Black Seas, Japan, the Koreas, and Australia.



Emission Control Areas
Source: DNV-GL

BALLARD

Ports are often an intersection of marine, trucking, and rail operations, and the intensity of generated emissions are damaging to the local communities and environment. Governments recognize that these ports are a significant contributor to local air pollution and GHG emissions, and are now working to reduce and eliminate harmful emissions.


Port Angeles Harbor, WA (USA)

Some ports, including the San Pedro Bay Ports (Port of Los Angeles and Port of Long Beach) in California, have already adopted emission regulations, including upcoming zero-emission requirements for trucks and port equipment. These regulations promote the use of zero emission power, including batteries and hydrogen fuel cells, for drayage trucks, port equipment, vessel navigation within the port boundaries, vessel cold ironing, and other port applications.

Clearly, there is a pressing need for zero emission power to address marine propulsion, auxiliary and cold ironing requirements, while meeting environmental goals. The only options for ship-based zero emission power production are fuel cells and batteries (disregarding nuclear power).

ENERGY REQUIREMENTS

Ship power and energy requirements are a function of the vessel characteristics, voyage requirements and fueling frequency. The duty cycle (power requirement versus time) guides the vessel power system design, and the allowable fueling frequency impacts the possible choice of fuels and storage methods; less frequent fueling drives the need for fuels with higher energy density and/or larger fuel storage.

Fuel energy density may be quantified on either a mass-basis or volume-basis. Typical units for fuel energy density are MJ/kg and MJ/liter and, importantly, some fuels are dense from a gravimetric or volume perspective, but typically not both (refer to following section on fuels).

Power requirements for marine vessels are described below. Understanding vessel power requirements is necessary for developing a fuel cell strategy which can meet marine requirements.

Propulsion

Power for propulsion is transient and also varies widely between the classes of ships and applications. If the propulsion system is based on an electric architecture, electric power systems can be combined together to meet the total power requirement (e.g., hybrid architectures of battery and combustion engine, or battery and fuel cell, or combustion engine with fuel cell and battery, etc.).

As shown in the following table, propulsion power requirements range from approximately 150kW to nearly 100MW – a scale factor of more than 500.

Vessel Category / Application	Power Requirement, Approximate, MW
Ferries	
Small Ferries	0.24 – 1.0
Large Ferries, Inland Waters	2 - 12
Large Ferries, Open Seas & High Speed	20 -44
Freight Vessels	
Inland Freight Vessels, USA, Towed & Pushed Barges	0.13 – 1.0
Inland / River Vessels, Europe, Class 1 – Vb (Self-Propelled) & Push-Tow Barges	0.2 – 4.5
River Cruise Vessel, Class VIb	< 2
Tugs, Europe, Class 1	10
Inland Container Vessel, Mississippi River (proposed, 235m, up to 2960 TEU)	11.5
Cold Ironing (ports)	
Container Ships (5-13k TEU)	0.2 – 0.9
Cold Ironing; Tankers	Up to 3MW
Cruise Ships	
Cruise Ship, Hotel Load	3 - 10
Cruise Ship, Maneuvering in Port	20
Cruise Ship, Emergency Power	2 - 4
Cruise Ship, Propulsion	25 - 97

TEU = twenty foot equivalent unit

It is expected that a hybrid power system architecture consisting of fuel cell and batteries will be adopted for ferries and other vessels. The ratio of fuel cell to battery power will depend on the vessel, route and schedule. Hybrid systems can be designed so the fuel cells operate at steady state and the batteries are dimensioned for transient power requirements. The fuel cell can replenish the batteries during times when the vessel is at low power, for example while a ferry is loading or unloading in the slip. Maximum power can be delivered by the batteries and fuel cell working together, and cruising power can be delivered by the fuel cell.

Inland (river) vessels include barges pushed or towed by push boats and tugs, and self-propelled ships. In the US, a majority of inland commercial freight vessels are towed or pushed barges operating in river systems including the Mississippi, Columbia, and Sacramento, and the Gulf Coast and Great Lakes.

Inland River Vessel

In Europe, the commercial freight vessels on inland waterways is increasing, especially in Netherlands, Germany and France in an attempt to fight congestion around cities by shifting land transported freight to the inland water ways. The inland waterway freighters are characterized by slow and steady speeds.

Cruise ship power requirements can be larger than ferry power requirements due to the large size of the ships and the number of passenger berths and amenities.

The vessel power system must have the capability to deliver maximum rated power, but vessels are rarely operated at max power. The power system should be optimized for efficiency at the typical or average operating point. For propulsion, redundant energy systems are required. These points are important when considering possible zero emission power systems.

Power requirements for ferries and cruise ships vary widely depending on whether the ship is at berth or underway. However, even at berth, large ships may not shut down all power. Therefore, the power system should be selected for efficient operation over a wide power range.

Ballard can evaluate ship duty cycles to investigate and recommend the optimum hybrid architecture, fuel cell power, turn down requirements, fuel storage requirements, and estimated fuel consumption.

Propulsion power for deep-sea shipping is not considered in this paper because the supply of fuel needed for cross-sea zero emission shipping operations cannot yet be supported. However, deep-sea shipping can be supported with zero emission solutions for auxiliary power, cold ironing, or propulsion power while navigating close to shore and in ports.

Cruise Ship in Seattle Port (US)

Auxiliary Power

Auxiliary power for lighting, heating and air conditioning, instrumentation, emergency systems, galleys, and other systems is needed onboard both ferries and cruise vessels. Additionally, waste heat from the fuel cell could be put to beneficial use for water heating, laundry, or other purposes. And water produced by the fuel cell can be recovered if needed.

Cold Ironing

Ports, including the San Pedro Bay Ports, are requiring ships to shut off diesel engines while at berth. Power for hotel and other ship loads is supplied from shore power (electric grid) or could be provided by barges or shore-side systems of clean power generation; concepts for barges and mobile shore-side power systems based on fuel cell systems have been developed.

WHY FUEL CELL TECHNOLOGY IS THE RIGHT SOLUTION

Batteries can deliver power to the vessel from stored energy, but the battery quickly depletes and requires recharging to continue delivering power. Batteries can be an important component of hybrid power architectures where they are kept charged by an onboard generator (e.g., zero emission fuel cell). Batteries are heavy, and are difficult to scale-up for applications requiring high energy consumption since the only way to supply more energy is to add

Example 100kW Marine Fuel Cell Module

more batteries; practical limits on the mass of batteries (and cost) can be reached before the desired energy and autonomy is achieved. Therefore, batteries are most suitable for applications requiring low energy consumption or applications with duty cycles which allow the vessel to be taken “off-line” and recharged.

Fuel cells operating on hydrogen fuel are an efficient, environmentally-friendly, zero emission, direct current (DC) power source already applied to heavy duty bus, truck, and train applications, and are now under development for marine applications. The only emissions from a fuel cell are water vapor and some heat.

Fuel cells generate DC power compatible with modern ship electric and hybrid architectures, and may be deployed in parallel, dispatchable configurations to meet variable power requirements of vessels. And, if renewable hydrogen is utilized, fuel cells are a true well-to-wake zero emission power source.

Additionally, improved ship efficiency and reduced noise and vibrations are motivations for implementing fuel cell power.

Energy is stored in the fuel

Fuel cells are similar to a battery except that energy is stored in the form of a fuel; hydrogen, and as long as there is fuel, the fuel cell continues to convert the energy into power.

Rapid refueling

Refueling is typically rapid, and fuel tanks may be sized for the desired vessel autonomy. Buses and trucks are currently achieving hydrogen refueling times very similar to the speed of diesel refueling.

Scalability

Fuel cells are power-scalable to meet the power requirements of applications from work boats – to ferries – to large ships

Modular power system

Ship power systems are typically comprised of redundant systems. This enables optimizing fuel consumption to the load demand and offers resiliency in case of failure of a power system. Fuel cells nicely fit this requirement, as they may be combined into “modules”, and those modules can be operated efficiently and combined to meet the overall power requirement. Ballard’s PEM (proton exchange membrane) fuel cells are readily modularized and combined in parallel to provide the power and redundancy needed by the application.

Selection of the fuel cell stack and module designs (power, voltage, etc.) will depend on the target applications (e.g., power for emergency, or auxiliary, or propulsion, etc.) and ships.

WHAT FUELS TO ACHIEVE ZERO EMISSION?

The majority of marine fuels in use today are hydrocarbons derived from fossil sources, including petroleum and natural gas products. The use of these fuels results in air pollution and greenhouse gas emissions, whereas the use of renewable fuels fully contributes to meeting air pollution and greenhouse gas reduction goals.

Renewable fuels include bio-fuels and fuels, including hydrogen, produced from solar, wind and hydropower. Renewable hydrogen is produced from splitting water into hydrogen and oxygen using renewable electricity or reforming of bio-fuels. Other renewable fuels include ammonia (NH_3) produced from renewable hydrogen and atmospheric nitrogen, and synthetic fuels produced from renewable hydrogen and sequestered or atmospheric carbon dioxide (CO_2). These synthetic fuels include methanol and synthetic hydrocarbons. Additionally, LOHC (liquid organic hydrogen carriers) can be saturated with renewable hydrogen, and the hydrogen extracted when needed for the end application. For very large marine applications, LOHCs could be a useful carrier of hydrogen – in convenient liquid form.

Renewable hydrogen, generated from solar, wind, hydroelectric, and geothermal sources is considered an ideal fuel for decarbonizing society. It can be used for industrial purposes, power generation, heating, and as a transportation fuel. The conversion of renewable energy to hydrogen fuel is being demonstrated through various projects. In the Orkney Islands of Scotland, such a demonstration is well underway and is a model for the future, where renewable hydrogen is locally produced on the islands and used for transportation applications including powering a ferry boat (refer to HySeas III project below).

However, for widespread marine use, the production of renewable hydrogen requires scaling-up to meet energy demand of ships. Likely, while the supply and fueling infrastructure is developing, the initial use of fuel cells in the marine economy will be for lower power applications since such lower power applications will require lower quantities of fuel. These applications include propulsion of smaller vessels, powering auxiliary loads on larger vessels, or shore power applications. On cruise vessels, initial fuel cell applications could include generation of auxiliary power for hotel loads, emergency systems, and a portion of the propulsion power. Eventually, to achieve the desired phase out of GHGs in this century, fuel cells will likely power the complete ship.

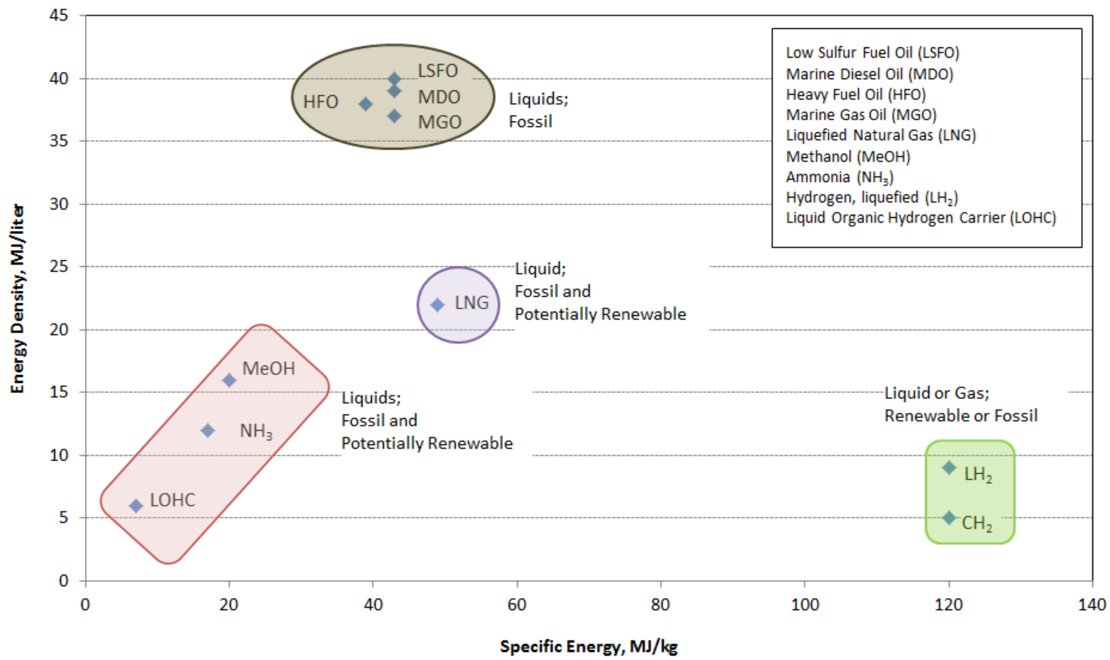
To support zero-emission marine power, ports will develop or secure supplies of renewable hydrogen, “carriers” of renewable hydrogen (refer to LOHC below), or synthetic fuels based on renewable hydrogen. Additionally, bunkering procedures and equipment for transferring these fuels to ships will be developed.

It is understood that the weight, volume and handling of fuels onboard ships are important considerations. In these respects, renewable hydrogen presents some conveniences compared to traditional marine fuels, but also some challenges. Compared to petroleum fuels, hydrogen is light weight and energy dense, it is not contaminated by microbes, there is no requirement for fuel-heating systems, no clean-up of sludge residues, no concern for environmental spills, and hydrogen could be completely renewable.

Port of Vancouver (Canada)

However, on a volumetric basis, hydrogen is not naturally energy dense; it must be compressed, liquefied, liquefied and compressed (cryo-compressed), or absorbed onto molecules for transport and storage with subsequent dehydrogenation when the hydrogen is needed. The energy content of current marine – and some possible future – marine fuels are shown in the following graph.

Marine Fuels Comparison



Whereas hydrogen, compared to conventional marine fuels, has a high gravimetric energy density – approximately three times higher – the volumetric energy density is approximately one-eighth to one-quarter. This combination of hydrogen properties could present problems for some vessels in some applications that cannot support large volume fuel storage or higher frequency refueling. Because of this, the industry is studying the best fuel choice which meets vessel, operational and emission requirements.

Synthetic hydrocarbon fuels and hydrogen carriers, including ammonia, methanol, and LOHCs (liquid organic hydrogen carriers) are an interesting area of research and development. Synthetic fuels may be produced from the combination of atmospheric or sequestered CO2 and renewable hydrogen or, in the case of ammonia, atmospheric nitrogen and renewable hydrogen. And, in the case of LOHCs, an organic liquid is hydrogenated and becomes a convenient "carrier" and long term storage mechanism for hydrogen. These fuels (methanol, anhydrous ammonia, and LOHCs) are attractive because they can be handled as liquids under atmospheric pressure, or in the case of ammonia, moderate pressure.

Initial marine applications that can support higher frequency fueling are potentially suitable for compressed or liquid hydrogen with fuel cells. This includes some coastal and river vessels, and ferries. Additionally, as noted above, applications that consume lower quantities of fuel, such as powering auxiliary loads on larger vessels (e.g., cruise ships), navigating in ports, or shore power can be early users of compressed or liquid hydrogen and fuel cells. Ballard believes these applications will be the start of an eventually decarbonized marine sector.

BALLARD

BALLARD FUEL CELL POWER SOLUTIONS FOR MARINE APPLICATIONS

Ballard fuel cells are a zero emission, high efficiency, low maintenance, scalable source of electric power, and it is expected that they will be an important solution for achieving the emission reductions required by the marine industry. Ballard fuel cells have already demonstrated operation of, without replacement or rebuild of the stack, more than 30,000 hours in heavy duty transit applications, and are deployed in difficult environments from desert to snow and cold.

With a nascent fuel supply and infrastructure, the initial focus of hydrogen and fuel cells in marine applications must be on vessels or applications with defined routes or points of operation. This focus will avoid the complexity and poor return on investment of a widely-dispersed fuel supply with (initially) correspondingly low throughput and utilization. As the market develops, the fuel supply and infrastructure will also thoughtfully be developed.

For smaller vessels with sub-megawatt power requirements, Ballard foresees synergy with our existing and future heavy duty fuel cell modules which are already deployed in bus, truck, and rail applications. A specific marine fuel cell power module of 200kW is currently being developed by Ballard.

Multiple 200kW blocks, electrically-configured in parallel, will provide efficient, dispatchable vessel power up to 1MW.

Power for larger vessels will be guided by input from Ballard's industry partners and is expected to be based on building blocks of approximate 1 to 3MW power. These blocks are expected to be synergistic with our existing ClearGen® stationary power systems, with a focus on efficiency and favorable life cycle costs. Those blocks may also be electrically-configured in parallel to provide power up to multi mega-watts.

BALLARD MARINE PROJECTS

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.

FLAGSHIPS

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 HD fuel cell modules for maritime applications. Collaboration with industry partners is important for improving integration into the vessel propulsion system.

H2PORTS

This project introduces hydrogen as an alternative fuel for heavy duty port equipment in the port industry. The aim is to provide efficient solutions to facilitate bridging the gap between prototypes and pre-commercial products. The project will include the deployment of fuel cells in a Reach Stacker, a Yard Tractor and the installation of a refueling station in the Port of Valencia.

The advantages of hydrogen as a zero emission fuel for heavy duty applications, as well as the flexibility of Ballard's HD fuel cell module will be demonstrated by integrating the module into a Reach Stacker and Yard Tractor.

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 fueled by hydrogen. The fuel cell technology will allow for faster refueling and longer distance between refueling 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).

HFC Marine Concept

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.

SHIPPINGLAB

The Shipping Lab project is a part of the Danish and worldwide merchant fleets transition towards greener shipping. The core elements in the project are Autonomous shipping (WP1), Digitalization (WP2) and Decarbonization (WP3). 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 separates into three work packages, each of which addresses a key requirement for the future ship. Synergies exist between WP1 and WP2 on data standards and sharing of digital twin models, between WP1 and WP3 on operational models for definition of test cycles as well as fuel reduction needed for the decarbonization agenda. In WP2 and WP3, technology for the future autonomous and CO2-neutral ship is developed and demonstrated in a live environment. WP4 coordinates and secures communication.

Shipping Lab

Ballard will learn about deploying hydrogen and fuel cells in port applications and will demonstrate the power and flexibility of fuel cell modules by integrating HD modules into a 300kW shore power package for vessel cold ironing.

HYSEAS III

The HySeas III project (www.hyseas3.eu) 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 emissions 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 emissions ferry with landside infrastructure to provide the hydrogen and realization of the associated economic and environmental benefits.

Ballard will participate in safety-approval of fuel cell solution, will work on integration with vessel architects and ship builders, will provide fuel cell modules of approximately 700-800kW for the ferry, and will develop operational lifecycle procedures.

HYSEASIII Fuel cell powered ferry (Scotland)

SUMMARY

There is a clear need and imminent requirements for reducing greenhouse gas emissions from ships and port operations. Fuel cell systems using renewable fuels including hydrogen are the most viable and scalable true zero emission solution for marine vessels. Furthermore, fuel cell systems offer the ship builder and operators the advantages of high efficiency, modular design for redundant and dispatchable power, DC power output, long lifetime, and rapid refueling.

Ballard is well-positioned to address the zero emission needs of the marine industry and is currently engaged in several projects with major marine industry stakeholders to develop fuel cell marine solutions and demonstrate the advantages of fuel cells and hydrogen for ships and port operations using renewable hydrogen fuel.

For more information please contact Ballard's Marine Fuel Cell Experts:

Ballard Power Systems Inc.
www.ballard.com
marketing@ballard.com

Ask a Fuel Cell Expert