Fuel cells in commercial marine applications

Recently, proton exchange membrane fuel cells (PEMFC) have emerged as the preferred solution in transportation applications, and there are already several marine projects with PEMFC under development. Experience gained from small-scale installations can be utilized in larger ships, as development and demonstration of megawatt-scale fuel cell solutions is already in progress.

DR. SAMI KANERVA
Global Product Manager
Fuel Cells
ABB Marine & Ports

KLAUS VÄNSKÄ
Head of Global Strategy and Business Development
ABB Marine & Ports

HANSUELI KRATTIGER
Business Developer
ABB

The need to cut emissions from seaborne traffic is guiding shipowners to apply alternative fuels and fuel cell systems in their vessels. Fossil fuels can be partly replaced by bio-based and synthetic fuels, as they can be used in combustion engines directly or following modifications. The introduction of synthetic fuels also requires ramping up hydrogen production, which in turn enables implementing efficient fuel cell systems for producing electrical power for the shipboard power systems.

Introduction

In 2018, the International Maritime Organization (IMO) adopted an initial strategy to reduce greenhouse gas (GHG) emissions from ships [1]. In the first stage, targets were set to reduce CO2 emissions per transport work by 40 percent by 2030 and total GHG emissions from shipping by 50 percent by 2050. The IMO strategy will be revised in 2023, defining specific short-term measures and outlining mid- and long-term measures to achieve the targets by 2030 and 2050.

Based on the GHG reduction targets above, DNV has presented a forecast for maritime transport going towards 2050 as part of their Energy Transition Outlook 2019 report [2]. Seaborne trade is expected to continue growing until 2035, but several measures are anticipated to cut emissions already around 2025, as illustrated in Figure 1. Logistics, energy efficiency and speed reduction will have an impact, but the transition from fossil to renewable fuels is inevitable if targets set by the IMO are to be met. The gap to be closed by fuel transition is around five percent in 2030 and nearly 50 percent in 2050.

With a generally accepted 20-30 year life cycle for ships, the transition to renewable fuels must take place at a rapid pace if these goals are to be met. Backward calculation of the CO2 reduction shows a need of 200,000 GWh of carbon-free energy per annum in 2030. In order to utilize this fuel, approximately 40-50 GW of new machinery needs to be installed as well. This will place massive pressure on newbuild projects, as well as creating demand for converting or retrofitting existing machinery in order to meet the GHG targets in time.

Although LNG will aid the transition in the beginning, it will not provide the final solution. Hydrogen and fuel cells together present an interesting solution for emission control, since the fuel itself is free of carbon, and the absence of combustion in fuel cells also keeps the exhaust free of nitrogen oxides.

According to the annual review by the fuel cell industry [3], production of proton exchange membrane fuel cells (PEMFC) underwent a dramatic increase during 2015-2019. This was due in large part to demand from the automotive industry, but the interest in marine applications is nonetheless on the rise.

The growth of marine fuel cell projects started with demonstrator projects, applying fuel cell modules originally developed for buses and trucks, typically with installations between 100 kW and 600 kW on small vessels. A few hydrogen concept vessels have received funding as well, and projects have shown increasing trends in power capacity. Behind the scenes, there are many projects in the planning stages, confirming the trend.

When applying fuel cells to larger ship solutions, several challenges have yet to be addressed. To begin with, safety concepts for new fuels and systems must be developed. Considerable changes in the general onboard arrangement may also be expected, and the basic principles of ship design may even need to be challenged. Fuel storage and machinery present different space requirements with fuel cells than in conventional systems. Reconsidering heat recovery concepts will also be needed due to considerations regarding cryogenic systems and low-temperature exhaust.

The regulatory landscape on hydrogen is still somewhat immature, since administrative regulations and class rules are still under development. The international code of safety for ships using gases or other low-flashpoint fuels (IGF code) [4] from the IMO is the main guideline to be applied, although at present it offers detailed rules only for LNG. Revisions for other gaseous fuels are pending, but it will take years to complete the code to include hydrogen-related regulations. However, classification societies are developing guidelines in collaboration with flag state authorities in order to create a predictable roadmap and support shipowners with the alternative design process for flag state approval.

Renewable scenarios

Although targets for emission reduction have been widely adopted, there are still several alternative pathways open for meeting targets on a global scale. A study by University Maritime Advisory Services (UMAS) presents various carbon reduction scenarios related to regulations, fuel availability and cost development [5]. The report concludes that reduction of carbon intensity in shipping will require a transition to bio-based or synthetic fuels in addition to energy efficiency interventions. The role of hydrogen and hydrogen-based fuels in shipping varies widely between the different pathways, presenting a share between 30 and 60 percent in the most likely scenarios. The share of biofuels vary between 10 and 20 percent in most scenarios.

Representing an even higher level of ambition, the Energy Watch Group (EWG) and Lappeenranta University of Technology (LUT) offer a pathway to shift globally to 100 percent renewable energy

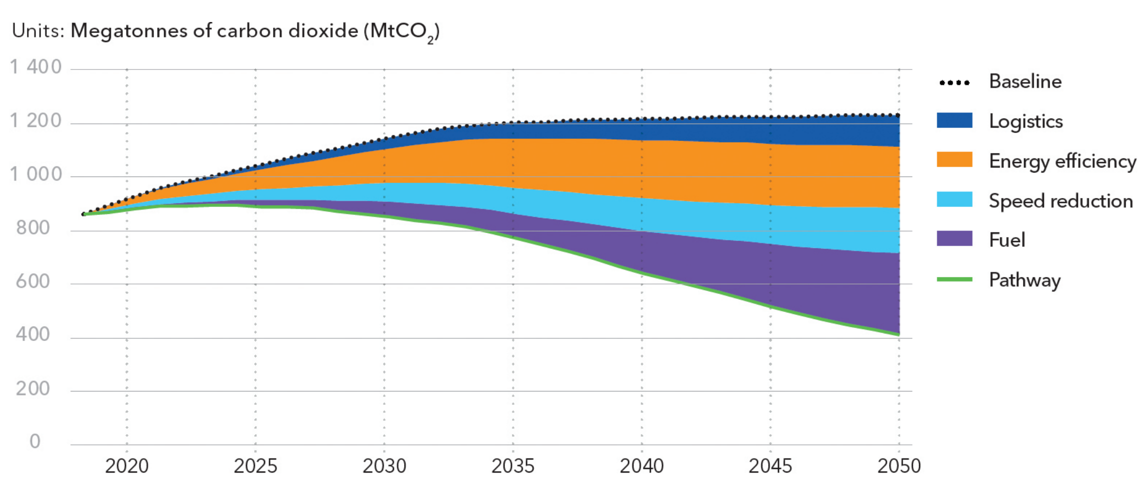


Figure 1: Shipping emissions reduction by measure (2018-2050) [2]

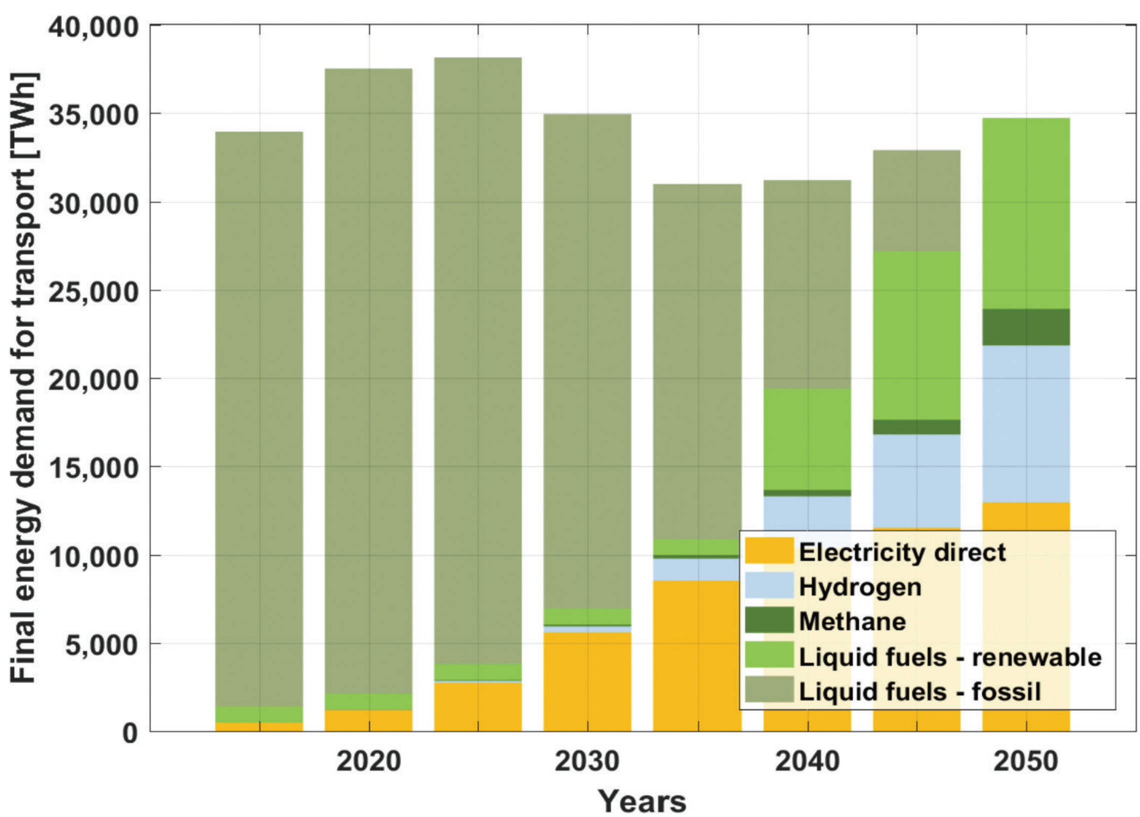
in all sectors [6]. In the transport sector, of which shipping is a substantial part, use of hydrogen would be ramped up between 2025 and 2050. As presented in Figure 2, liquid renewable fuels and hydrogen would together eventually represent more than half of the total energy demand in the transport sector.

Alternative fuels

The International Energy Agency (IEA) has examined the availability and potential market for biofuels in the marine sector in a research perspective [7]. Current production capacity for biofuels is far below the potential need in the maritime sector, and even with considerable ramp-up of production, biofuels could only partially support decarbonization targets. Biodiesel derived from plant oil or pulping residues could be produced at relatively high capacity, and can be used as drop-in fuel blended with marine diesel. Bioethanol can be produced with an even higher supply potential, although this would require modifications in machinery in order to be used with combustion engines.

In addition to biofuels, it is possible to produce synthetic hydrocarbons from hydrogen and carbon dioxide, or ammonia with nitrogen [8]. These synthetic fuels, also known as e-fuels, have a carbon footprint relative to the feedstock and energy used in the production process. Producing carbon neutral e-fuels requires that hydrogen originate from e.g. water electrolysis. Carbon dioxide is captured from industrial flue gases or directly from air, and the energy for the production process is supplied from renewable sources.

Potential carbon-based e-fuels include methane, methanol, diesel and jet fuel, all of which could be used directly with conventional machinery or blended with existing fuels. However, the development initiatives for e-fuel production are still at the demonstrator level, and even after scaling up to commercial quantities their production cost will be substantially higher than current fossil fuels. Hence, it is widely considered that the most prominent e-fuels in the medium and even long term would be non-carbon alternatives, i.e. ammonia and hydrogen [2][5][6][8].



—
Figure 2: Energy demand for the transport sector to meet the pathway to 100 percent renewable energy [6]

Since hydrogen is the primary feedstock for all synthetic fuels, a massive ramp-up of hydrogen production is inevitably needed for large-scale production of synthetic fuels. As hydrogen is also applicable as primary fuel, it is anticipated that simpler production chains and logistics will favor hydrogen over other e-fuels. In the long term, hydrogen is also expected to have substantially lower cost than other e-fuels due to its simple production process [6][8].

Fuel cell technologies

Compared to combustion engines and gas turbines, fuel cells provide higher efficiency without NOx emissions. With few moving parts in the system, they are quiet and reliable. For these reasons, fuel cells provide a very competitive means of utilizing hydrogen as fuel in ships with electric propulsion.

Fuel cell technologies for shipping are reviewed in the study by the European Maritime Safety Agency (EMSA) and DNV [9]. Alkaline fuel cell (AFC) technology has a long history from the space shuttles, and costs are relatively low. Proton exchange membrane fuel cell (PEMFC) technology is widely used in transport applications. Its main advantage is high power-to-weight ratio. Both technologies utilize only pure hydrogen as fuel, and operate at relatively low temperatures.

Phosphoric acid fuel cells (PAFC) operate at temperatures up to 200°C and can also support heat recovery systems. Molten carbonate fuel cells (MCFC) and solid oxide fuel cells (SOFC) both operate at temperatures higher than 500°C. Direct methanol fuel cell (DMFC) technology allows the use of methanol as fuel without a separate reformer. Both MCFC and SOFC can operate with flexible fuels due to integrated reforming processes, and PAFC can also run on LNG or methanol with an external reformer.

The development of the fuel cell market during 2015-2019 is illustrated in Figure 3. Over last five years, PEMFC has experienced continuously increasing growth, while the annual market for other technologies has remained constant. Growth is mainly due to demand from the automotive industry, which favors the compact size, reliability and lifetime expectancy of PEMFC. In addition to automotive applications, the same benefits apply for heavy transport and marine. Accordingly, increasing capacity of PEMFC would indicate decreasing production cost in the near future for all industries, including marine.

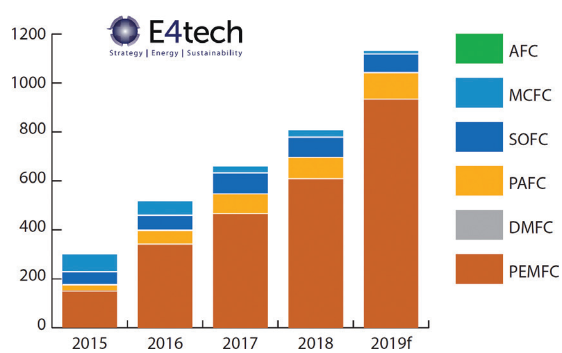


Figure 3: Annual production volumes (megawatts) for different fuel cell technologies during 2015-2019 [3]

Project	Year	Fuel cell power	Fuel
Maritime container	2017	100 kW	H2
RCCL demonstrator	2017	100 kW	H2
Cargo vessel in France	2021	400 kW	H2
Ferry in Norway	2021	600 kW	H2

Table 1: Examples of marine PEMFC projects

Selected marine projects with fuel cells

Sandia National Laboratories started a project in 2013 to design and build a containerized hydrogen fuel cell generator for maritime use [10]. The maritime fuel cell generator is powered by a 100 kW fuel cell system from Hydrogenics and includes storage for pressurized hydrogen. The container was upgraded with power conditioning and control systems from ABB in 2017. Similarly, Royal Caribbean Cruise Lines (RCCL) presented a 100 kW demonstrator at RCCL Technology Display Days in 2017. The event was powered by the fuel cell system engineered and developed by ABB and Ballard Power Systems.

Another example is an EU-funded project, FLAGSHIPS, was awarded EUR 5 million of funding in 2018 from the EU's Research and Innovation programme Horizon 2020, under the Fuel Cells and Hydrogen Joint Undertaking (FCH JU), to deploy two hydrogen vessels in France and Norway [12].

In other long-term research programs, the HySeas III project aims to launch a hybrid passenger ferry for operation in the Orkney Islands, Scotland [13], and Sandia National Laboratories published a feasibility study on SF-BREEZE concept in 2016, which has continued as Water-Go-Round ferry project planned for launch in 2021 [13][15]. There are also other fuel cell projects going on in Norway, France and the Netherlands, targeting hydrogen powered vessels with propulsive power up to 1 MW or slightly above.

Solutions for large ships

Existing fuel cell references have thus far been applied on smaller vessels, but most of the principles are also applicable to larger ships with large fuel cell power plants. Several marine stakeholders are conducting larger-scale fuel cell solution studies, although these have not yet been published. Safety concepts for hydrogen are similar for small and large vessels, and many of the rules or design guidelines originate from the experience gained from LNG. The double barrier principle from LNG systems is to be applied to hydrogen supply lines. Hydrogen is flammable or explosive in a wider range than LNG, and more focus should be placed in leakage detection scenarios. As the regulatory landscape is not complete for hydrogen, the ships must generally follow the approval path for alternative design.

Integrating fuel cells into the electrical distribution network follows the same principles with both small and large vessels. In order to form power-generating units of convenient size and voltage, the fuel cell stacks can be connected electrically in parallel and in series. DC/DC converters are generally required for regulating the load-dependent output voltage from fuel cells to a constant value. Connection to an AC network is carried out by a DC/AC converter and transformer in order to ensure galvanic isolation and the correct voltage level. Integration with a DC network saves cost and space due to reduced equipment requirements, although implementation of DC networks in large vessels still requires further development of medium voltage DC distribution technology.

In the commercial shipbuilding market, there is a clear interest in designing and building fuel cell ships, also in the megawatt range. With such ratings, it is no longer feasible to compose large fuel cell systems from modules of a few hundreds of kilowatts. ABB and Ballard Power Systems announced in 2018 their collaboration on jointly developing marine-specific MW-scale fuel cell units. Following the announcement from ABB and Ballard, other consortiums have been formed to develop large-scale fuel cell systems for marine use. It is expected that the first demonstrators of such systems will be running onboard operating ships within 2023-2025.

Considerations for ship design

One of the main challenges with hydrogen fuel cells is the space required for hydrogen storage. On a large scale, the most feasible solution is to use liquified hydrogen (LH2), where the technology for cryogenic storage is modified from known LNG solutions. For cases with limited available space for fuel storage, original feedstock may be stored in the form of another fuel and reformed into hydrogen by a specific reformer or utilizing auto-reforming fuel cell technology.

Selection of primary fuel and fuel cell technology should be made at an early stage of the ship design process, since it may have notable effects in the power balance and general arrangement. For instance, low exhaust temperature in fuel cells may limit the use of heat recovery, but also free up valuable space due to reduced need for insulation. On the other hand, a cryogenic system may be utilized for cooling with high efficiency, as the heat for the vaporizer can be extracted from the air conditioning system.

The general arrangement of a hydrogen ship may be significantly different from a conventional vessel. Because of the low-temperature exhaust from e.g. PEMFC, the amount of thermal insulation in exhaust air channels is substantially lower compared to combustion engines. Accordingly, more payload can be added in the upper deck area. Additional freedom is also gained for the general arrangement of machinery spaces, since the fuel cell units are flexible in shape and can be distributed around the hull. This also simplifies distributing the power plant into independent sections.

Hybrid solutions

Ongoing fuel cell projects will help to resolve several challenges related to hydrogen and fuel cell installations. A natural movement towards larger fuel cell ships would be to apply fuel cells in hybrid power systems, where fuel cells are installed in parallel with battery systems or conventional generator sets.

Hybrid vessels can operate in zero-emission mode when idling or operating close to a harbor. An additional feature of the hybrid fuel cell power plant is silent operation using fuel cells, and batteries when needed. Internal combustion engines or gas turbines can still be utilized to produce high power for the system when there is need for high speed or other high-power applications.

Solutions for naval ships

Regarding naval ships, lessons learned from commercial projects will be useful when considering alternative fuels and fuel cells. For instance, combatants typically have high installed power with very specific requirements to deal with more dynamic loads and survivability compared to commercial projects. However, fuel cell systems for such naval applications would not be very different from those of commercial ships.

Conclusion

The emerging need for decarbonization has been widely acknowledged in the marine sphere, and the IMO has adopted ambitious targets to cut emissions dramatically by 2030 and 2050. Accordingly, alternative fuels and fuel cell systems for carbon-free electricity production have gained traction among shipowners and shipyards.

On a short to medium timescale, PEMFC technology supplied by hydrogen is likely to be the leading selection for marine fuel cell systems. Nevertheless, high-temperature technologies able to utilize other fuels like SOFC and DMFC may break through eventually. The market for marine fuel cell applications has evolved from technology demonstrators to the smaller ship segment for hydrogen power propulsion systems. In the next phase, fuel cell systems are expected to be developed in the megawatt range, able also to power larger vessels.

However, there are other considerations related to ship design when implementing hydrogen fuel cell systems on large ships. For instance, the low temperature of exhaust air places restrictions on heat recovery, but allows for more flexibility of the general arrangement. Fuel storage and supply systems are also slightly different from conventional systems. Nevertheless, there are no major obstacles to the application of hydrogen and fuel cells in large ships, while some engineering challenges remain to be solved.

—

References

[1] Initial IMO strategy on reduction of GHG emissions from ships, International Maritime Organization, Resolution MEPC.304(72), April 2018.

[2] Energy Transition Outlook 2019, Maritime Forecast to 2050, DNV GL, September 2019.

[3] The fuel cell industry review 2019, E4tech, December 2019.

[4] International code of safety for ships using gases or other low-flashpoint fuels (IGF code), International Maritime Organization, Resolution MSC.391(95), June 2015.

[5] Smith, Raucci, et al., CO2 emissions from international shipping. Possible reduction targets and their associated pathways, UMAS, October 2016.

[6] Ram, Bogdanov, et al., Global Energy System based on 100 percent Renewable Energy – Power, Heat, Transport and Desalination Sectors, Lappeenranta University of Technology and Energy Watch Group, March 2019.

[7] Hsieh and Felby, Biofuels for the marine shipping sector, University of Copenhagen and IEA Bioenergy, October 2017.

[8] Yugo and Soler, A look into the role of e-fuels in the transport system in Europe (2030-2050) (literature review), Concawe Review, Vol 28, No 1, pp. 4-22, October 2019.

[9] Study on the Use of Fuel Cells in Shipping, European Maritime Safety Agency and DNV GL, January 2017.

[10] Maritime Fuel Cell Generator Project, Sandia Report SAND2017-5751, Sandia National Laboratories, May 2017.

[11] MARANDA research project website, available online: https://projectsites.vtt.fi/sites/maranda/www.vtt.fi/sites/maranda.html [accessed 05/07/2020].

[12] FLAGSHIPS research project website, available online: https://flagships.eu [accessed 05/07/2020].

[13] HySeasIII research project website, available online: https://www.hyseas3.eu/ [accessed 05/07/2020].

[14] Feasibility of the SF-BREEZE: a Zero-Emission, Hydrogen Fuel Cell, High-Speed Passenger Ferry, Sandia Report SAND2016-9719, Sandia National Laboratories, September 2016.

[15] Water-Go-Round project website, available online: https://watergoround.com/ [accessed 05/07/2020].

Originally presented at the ASNE TSS 2021 virtual conference