The potential of fuel cells as a drive source of maritime transport

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Abstract. The state of environmental pollution brought about as a result of the modern civilization has been monitored, in the interests of the environment and human health, since the seventies of the last century. Ensuring the energy security is one of the most basic existential requirements for a functional civilized society. The growing civilizational needs caused by broadly understood development generate demand for the production of all kinds of goods in all sectors of the economy, as well as world-wide information transfer. The current energy demand is mostly covered using fossil fuels such as coal, oil and natural gas. Some of the energy demand is covered by the energy generated in nuclear reactions, and a small part of it comes from renewable energy sources. Energy derived from fossil fuels is inevitably associated with fuel oxidation processes. These processes, in addition to generating heat, are responsible for the emission of harmful compounds to the atmosphere: carbon monoxide, carbon dioxide, nitrogen oxides, hydrocarbons, and particulate matter. These pollutants pose a serious threat to the people as well as the environment in which they live. Due to the large share of fossil fuel energy generation in the process of combustion, it becomes necessary to seek other means of obtaining the so-called "clean energy". Fuel cells may have a very high potential in this respect. Their development has enabled attempts to use them in all modes of transport. An important factor in the development of fuel cells is their relatively high efficiency and the coinciding strictening of the emission norms from internal combustion engines used to power maritime transport. Therefore, the aim of this article has been to assess the potential of fuel cells as a main source of propulsion power source. A review of the designs of fuel cell systems and their use was performed. The article summarizes the assessment of the potential role of fuel cells as a power source of maritime transport.

1. Introduction
Increasing energy demand is associated with increased emissions of many harmful substances such as carbon dioxide, nitrogen oxides, particulate matter and carbon monoxide, grid oxides and hydrocarbons [1-7, 10, 12-14, 17- 21]. The technologies used for generating energy are characterized by relatively low efficiency ratios (Figure 1), while fuel cells outperform existing power plants and internal combustion engines. From one cell a voltage of 0.6 to 1 V is obtained at a current of 0.111 A/cm\textsuperscript{2}. Depending on the electrolyte used and the operating temperature most commonly used in the transport areas are low temperature cells.
High temperature fuel cells due to working conditions (temperature of 500–1000°C) have been used in stationary systems, as opposed to low temperature cells, whose operating temperature allows them to be used in transport [18]. Low temperature cells SOFC are mainly used as stand-alone systems with an electrical efficiency of 60% [16], whereas high temperature cells in cogeneration with gas turbines allow for efficiency of over 70% [16]. The SOFC cell needs to supply pure hydrogen or carbon monoxide. The use of onboard reforming for the production of hydrogen from diesel fuel enables the efficiency of the cell to reach 45–55% [10] or from 45–60% natural gas [20]. Yousri et al. [24] have shown that the SOFC cell allows for 0.8 V at 100 mA/cm² current density, with a single cell efficiency of 43%.

Fuel cell systems are known not only for their high efficiency and low emission but also for low noise emissions. The downside, however, is their high cost of production, closely linked to the small scale of production and its technological characteristics. The service life of fuel cells is very important. The performance of the fuel cell stack indicates that continuous operation and cleanliness of the fuel used to power the cells is essential for long service life and high efficiency. The availability of fuel is crucial in the spread of fuel-based systems, especially in maritime transport. Due to the above problems, strategies for the use of fuel cells in vessels have been developed for many years.

2. Fuel cells

One of the drive system concepts using alternative fuel are the so-called hybrid systems, where fuel cells are used instead of an internal combustion engine. Fuel cells differ from each other in structure, the materials used in their construction and the efficiency of energy production depending on which fuel they use (Table 1) [8, 18]. The classification of fuel cells is based on the electrolyte used in the cell. The used electrolyte determines the temperature of the reaction occurring in the fuel cell and fuel cell power. Each cell has advantages and disadvantages, which define the field of application for each type of cells.

PEM fuel cells (Proton Exchange Membrane or Polymer Electrolyte Membrane) are powered with pure hydrogen or reformate. PEM cell membrane is a polymeric material, such as nafion. A characteristic feature of the PEM cell is a high electricity production efficiency – up to 65% and a small amount of heat. An important advantage of PEM cells is good response time of cell systems.
subjected to variable loads and short start-up time. These characteristics result from the low temperature reaction occurring in the cell – at 60–100°C.

AFCs (Alkaline Fuel Cell) use a KOH solution as an electrolyte. The reaction takes place at temperatures from 100 to 250°C. The reaction temperature depends on the KOH solution concentration, higher reaction temperatures can achieve higher cells electricity and heat generation efficiency. AFC cells are sensitive to any contamination and require fuel with a high degree of purity.

DMFCs (Direct Methanol Fuel Cell) have a polymer membrane, similar to PEM cells. But a different structure of the anode, which in DMF cells enables an internal reforming of methanol, and creation of hydrogen to feed the cells. DMF cells eliminate the problem of fuel storage and are attractive for portable applications due to the low reaction temperature (about 80°C). DMF cell is characterized by lower efficiency compared to the PEM cell, at only 40%.

PAFCs (Phosphoric Acid Fuel Cell) are used to build systems of cogeneration of electricity and heat. The efficiency of electricity generation is about 40%, in addition the water vapor produced by the cell can be converted to heat. The electrolyte in the PAFC cells is phosphoric acid (H₃PO₄). The advantage of these cells is a high tolerance to carbon monoxide, which makes them suitable for multifuel use (desulfurization of fuel is important, however).

MCFCs (Molten Carbonate Fuel Cell) in which the electrolyte is a molten Li/K carbonate operate at high temperatures and are used for the production of electric and thermal power as small and medium power sources. Large temperature of the reaction occurring in the fuel cell allows it to use a variety of fuels, including natural gas, gasoline, hydrogen, and propane.

SOFCs (Solid Oxide Fuel Cell) have a membrane made of an oxide ceramic. They operate at high temperatures 650–1000°C. This way they reach a high efficiency in electricity and heat cogeneration systems, as high as 85%. The disadvantage is the start and shut down time of the cell, which is reflected in their use in stationary CHP systems (Cogeneration Heat and Power). SOF cells have a high tolerance to fuel contaminants such as carbon monoxide and sulfur compounds, which allows them to use multiple fuel types.

| Table 1. Fuel cell characteristics comparison [1, 8, 18] |
|---------------------------------|--------------|-------------------|
| Cell type                        | Fuel          | Operating temp.    | Eff.          |
| PEM (Proton Exchange Membrane)   | Hydrogen      | 60–100°C          | 35 – 60%      |
| AFC (Alkaline Fuel Cell)         | Hydrogen      | 100–250°C         | 50 – 70%      |
| DMFC (Direct Metanol Fuel Cell)  | Methanol      | 75°C              | 35 – 40%      |
| DMFC (Direct Methanol Fuel Cell) | Methanol solution |                |               |
| PAFC (Phosphoric Acid Fuel Cell) | Hydrogen      | 210°C             | 35 – 50%      |
| MCFC (Molten Carbonate Fuel Cell)| Hydrogen, methanol, methane, biogas, LPG | 650°C          | 40 – 50%      |
| SOFC (Solid Oxide Fuel Cell)     | Hydrogen, methanol, methane, biogas, LPG | 650–1000°C     | 45 – 60%      |

3. Fuel cell potential for use to power ships

The characteristics of the fuel cells and the indications for their operation are in line with the operating characteristics of the vessel. This in particular concerns the required continuous process of operation. In addition, it is becoming increasingly important to reduce the negative impact of transport on the environment, including on maritime transport, and therefore many of the work involved in the use of fuel cells as a source of energy for both watercraft and power generators for the functional needs of ships. Depending on the destination function and the size of the vessel, energy generators using fuel cells must provide the required energy parameters. These are usually the requirements of high power values and the intensity of electricity. This requires the development and application of new technologies for the construction of power packs of cells that will enable high performance single
cells. This is a very difficult task because it involves the fuel supply, the output of the end products, the discharge of the generated electricity and, above all, ensuring adequate cooling not only of the cell stack, but also of the high temperature cells of the individual components of the cell. These problems are so important that so far many work is carried in this direction. These works involve the use of fuel cells in all areas of their applications, including in the applications of vessels. The intensity of the work depends on the intensity of support in the implementation of research and development projects conducted by companies and research units dealing with the use of fuel cells in watercraft (Figure 2 and Table 2) [9, 11, 22, 23]. The developed concepts included in the presented examples of projects, depending on their purpose, are within the range of power generation from several kW to 2.5 MW. All solutions concern the use of a modular power supply system with modules of 12–60kW and 120kW. The number of used modules generates the coupling potential of the energy source installed on the vessel. Most of the projects are focused on low-temperature, hydrogen-powered PEM cells. An interesting solution is the submersible power design of the Class 212A/214 Submarines, where the PEM cell is powered by hydrogen produced on board with methanol reformer.

![Figure 2. Number of fuel cell projects for ships since 2000 and fuel used.](image)

System is used in the HDW submarine drive Type 216 manufactured by Thyssen Krupp Marine Systems (Figure 3). The system operates on the principle of a steam reformer. Primary reforming reaction occurring in the device is as follows:

$$\text{CH}_3\text{OH} + \text{H}_2\text{O} \leftrightarrow 3\text{H}_2 + \text{CO}_2 \quad (1)$$

During the methanol reforming process a side reaction can also take place in the form of:

$$\text{CO}_2 + \text{H}_2 \leftrightarrow \text{CO} + \text{H}_2\text{O} \quad (2)$$
Table 2. Fuel cell projects for ships since 2000 [9, 11, 22, 23].

| Project Years (Main partners) | Concept | Fuel Cell and Capacity | Fuel |
|------------------------------|---------|------------------------|------|
| FellowSHIP 2003-2011 (Eidesvik Offshore, Wartsila, DNV) | 320 kW MCFC system for auxiliary power of Offshore Supply Vessel | MCFC 320 kW | LNG |
| Viking Lady - METHAPU Undine 2006-2010 (Wallenius Maritime, Wartsila, DNV) | 20 kW SOFC tested for the evaluation of 250 kW SOFC solution for marine APU. | SOFC 20 kW | Methanol |
| E4Ships – Pa-X-cell MS MARIELLA | 60 kW modularized HT-PEM fuel cell system developed and tested for the decentralized auxiliary power supply onboard passenger vessel MS MARIELLA. | HTPEM 60 kW (each stack is 30 kW) | Methanol |
| E4Ships - SchIBZ MS Forster | 100 kW containerized SOFC system developed and tested for the auxiliary power supply of commercial ships. Scalable up to 500 kW units. | SOFC 100 kW | Diesel |
| E4Ships - Toplanterne | Support of IGF Code development to include a FC chapter and set the regulatory baseline for the use of maritime FC systems | - | - |
| RiverCell | 250 kW modularized HT-PEM fuel cell system developed and to be tested as a part of a hybrid power supply for river cruise vessels | HTPEM 250 kW | Methanol |
| RiverCell – Elektra 2015-2016 (TU Berlin, BEHALA, DNVGL, etc.) | Feasibility study for a fuel cell as part of a hybrid power supply for a towboat | HTPEM | Hydrogen |
| ZemShip – Alsterwasser 2006-2013 (Proton Motors, GL, Alster Touristik GmbH, Linde Group, etc.) | 100 kW PEMFC system developed and tested onboard of a small passenger ship in the area of Alster in Hamburg, Germany | PEM 96 kW | Hydrogen |
| FCSHIP 2002-2004 (DNV, GL, LR, RINA, EU GROWTH program) | Assess the potential for maritime use of FC and develops a Roadmap for future R&D on FC application on ships | MCFC | Various |
Table 2. Fuel cell projects for ships since 2000[9, 11, 22, 23].

| Project Years (Main partners) | Concept | Fuel Cell and Capacity | Fuel |
|-------------------------------|---------|------------------------|------|
| New-H-Ship 2004-2006 (INE (Icelandic New Energy), GL, DNV, etc.) | Research project on the use of hydrogen in marine applications | - | - |
| Nemo H2 2012- Present (Rederij Lovers etc.) | Small passenger ship in the canals of Amsterdam | PEM 60 kW | Hydrogen |
| Hornblower Hybrid 2012- Present (Hornblower) | Hybrid ferry with diesel generator, batteries, PV, wind and fuel cell | PEM 32 kW | Hydrogen |
| Hydrogenesis 2012 - Present (Bristol Boat Trips etc.) | Small passenger ship which operates in Bristol | PEM 12 kW | Hydrogen |
| MF Vågen 2010 (CMR Prototech, ARENA-Project) | Small passenger ship in the harbour of Bergen | HTPEM 12 kW | Hydrogen |
| Class 212A/214 Submarines 2003 - present (CMR Prototech, ARENA-Project, ThyssenKrupp Marine Systems, Siemens) | Hybrid propulsion using a fuel cell and a diesel engine | PEM 306 kW, 30-50 kW per module (212A) 120 kW per module (214) | Hydrogen |
| US SSFC 2000 - 2011 (U.S. Department of Defens, Office of Naval Research) | The program addresses technology gaps to enable fuel cell power systems that will meet the electrical power needs of naval platforms and systems | PEM 500 kW MCFC 625 kW | Diesel |
| SF-BREEZE 2015 - present (Sandia National Lab., Red and White Fleet) | Feasibility study of a high-speed hydrogen fuel cell passenger ferry and hydrogen refueling station in San Francisco bay area | PEM 120 kW per module. Total power 2.5MW | Hydrogen |
| MC-WAP 2005-2010 (FINCATIERI, Cetana, OWI, TÜBITAK, RINA, NTUA, Techip KTI, etc.) | MC-WAP is aiming at the application of the molten carbonate fuel cell technology onboard large vessels, such as RoPax, RoRo and cruise ships for auxiliary power generation purposes | MCFC Concept design of 500 kW, final design of 150 kW | Diesel |
| FELICITAS – subproject 1 2005-2008 (Lürssen, FhG IVI, AVL, HAW, Rolls-Royce, INRETS, VUZ) | Application requirements and system design for FC in heavy duty transport systems | - | - |
Table 2. Fuel cell projects for ships since 2000 [9, 11, 22, 23].

| Project Years (Main partners) | Concept                                                                 | Fuel Cell and Capacity                                                                 | Fuel                                      |
|-------------------------------|-------------------------------------------------------------------------|----------------------------------------------------------------------------------------|------------------------------------------|
| FELICITAS – subproject 2 2005-2008 (Rolls-Royce, Uni Genoa, Lürssen, HAW, Uni Eindhoven) | Mobile hybrid marine version of the Rolls-Royce Fuel Cell SOFC system                 | SOFC 250 kW (60 kW sub system)            | LNG, other fuel also evaluated            |
| FELICITAS – subproject 3 2005-2008 (NuCellSys, FhG IVI, CCM) | PEFC-Cluster - improving PEFC reliability and power level by clustering | PEM Cluster system (80 kW basis component)                                             | Hydrocarbon fuels and hydrogen           |
| FELICITAS – subproject 4 2005-2008 (FhG IVI, Lürssen, NTUA, NuCellSys, CCM, Uni Belfort, AVL, CDL) | Power management – concerns general technical problems of FC-based propulsion | PEM                                       | -                                        |
| Cobalt 233 Zet 2007 - Present (Zebotec, Brunnert-Grimm) | Sports boat employing hybrid propulsion system using batteries for peak power | PEM 50 kW                                                                               | Hydrogen                                 |

This reaction is undesirable because of reduced efficiency of the hydrogen obtaining process. The resulting carbon monoxide fed to the cell impairs its efficiency and reacts with the platinum catalyst contained in the cell and can contribute to cell damage.

Figure 3. Methanol reforming system installed on a HWD type 216 submarine [15].

Therefore the process of reforming should be implemented with parameters ensuring maximum efficiency in obtaining hydrogen. Therefore the choice of catalyst and the process temperature, which may be 160–200°C is pivotal. In the reforming process carried out outside the fuel cell, it is important that the reforming temperature is less than the cell operating temperature. In this situation, the heat generated in the fuel cell can be used for the reforming process.

Similar problems with high cell efficiency are found with other MCFCs and SOFCs fueled by other fuels than pure hydrogen, such as LPG or diesel, which have to undergo internal reformation. A summary of the Fellow SHIP project in which the MCFC fueled by LPG is shown in February 2012, the total operation time had reached 18500 hours, with maximum expected operational time estimated to 24000 hours. The fuel cell stack has been running at constant loads, between 30mA/cm²
and 120mA/cm². A few tests challenging the dynamic response of the system has also been performed. The onboard test program measured a maximum electrical efficiency of 52.1% from the fuel cell stack at full load 330 kW. Exhaust gas testing was performed confirming predicted low emission levels of NOx and CO₂ [22].

Worth noting is US Ship Service Fuel Cell (US SSFC) project was run by the Office of Naval Research (ONR, U.S. Department of Defence) from 2000–2011 focusing on basic and applied research to address the gaps between the existing fuel cells and the requirements for fuel cells used in naval applications. The US SSFC includes evaluation and development of a 625 kW MCFC and a 500 kW PEM fuel cell both using diesel as fuel. Both systems are complete with supporting systems including diesel reforming, purification of the fuel prior to the fuel cell and a complex heat and energy recovery systems and systems for regeneration of catalyst. MCFC system has an efficiency of 53% and the PEM FC has an efficiency of 35%. A lesson from the project is that further scale-up is limited by the volume and complexity of the systems (figure 4) [22].

![Figure 4. Fuel cell and fuel processing system for a 625 kW MCFC module [22].](image)

In order to ensure the functioning of the fuel cell, a diesel reformer is needed, the resulting compounds are purified and separated in the Gas Cleanup System and then routed to the fuel cell. Fuel not used in the cell is burned in the combustion chamber and the resulting gases drive the turbocharger to deliver the air to the system with required parameters. The electricity produced by the fuel cell is processed to the required parameters. Current projects include the development and implementation of HTPEM high temperature fuel cells powered by Methanol E4Ships-Pa-X-ell – 60kW and RiverCell – 250kW. One E4Ships – Schibz 100 kW diesel fuel cell project. These projects concern the installation of fuel cells fueled by conventional fuels that undergo a reforming process for the fuel cell [9, 11, 22].

4. Conclusions
Considering the environmental impact resulting from the combustion of fossil fuels including methanol, characterized by the emission of carbon monoxide, hydrocarbons, nitrogen oxides and particulate matter, as well as the efficiency of the processes for producing mechanical energy for vehicle drive systems, it can be concluded that the use of methanol as a fuel for fuel cells can be a good alternative to the currently used conventional fuels. The concept of adopting methanol in a
function of a hydrogen carrier and storage is interesting from the perspective of ease of transporting and storing of fuel. But the key to this concept is the development of methanol reforming systems. With a high efficiency of the realized processes, a high hydrogen production efficiency, and system miniaturization, in combination with high efficiency fuel cells, these solutions may find use in the means of mass transport such as or various types of sea vessels. Therefore, with the currently observed rapid development of fuel cells, action should be taken to focus on the development of reforming systems and technology of high temperature cells construction.

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