Public final report: Inventory of the application of Fuel Cells in the MARitime sector (FCMAR)

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1. Introduction

There is a strong societal pressure to reduce harmful air emissions from shipping. This is not only true for Emission Control Areas (ECAs) near the coast, but also outside these areas deep sea ships have to comply to a stringent sulphur limit (< 0,5% Sulphur) from the 1st of January 2020 onwards[1]. Many ship owners have shifted or will shift towards Low Sulphur fuel oils in order to comply with the new regulations. Ultra-Low Sulphur Heavy Fuel Oil (ULSHFO), Low Sulphur Marine Gas Oil (LSMGO) and Liquified Natural Gas (LNG) can achieve a substantial reduction of Sulphur Oxides (SO_X) emissions. Gas engines and dual fuel engines can also achieve a substantial reduction in Nitrogen Oxides (NO_X) and Particulate Matter (PM) emissions. However, since all these alternatives are fossil fuels, they do not substantially contribute to the reduction of greenhouse gas (GHG) emissions like carbon dioxide (CO_2).

In the long term, ship owners will have to shift towards fuels that can be produced from renewable feedstocks (e.g. hydrogen, methanol and ammonia). Although practically any fuel can be used in an internal combustion engine, this is not the only way to convert the chemical energy into mechanical energy. For example, fuel cells (FCs) convert chemical energy directly into electrical energy through an electrochemical reaction, thus omitting the high temperature combustion process in engines. Therefore, fuel cells create the possibility to convert (renewable) fuels directly into electrical energy without emitting harmful exhaust gasses and can offer higher efficiency ratings than what is achieved by most internal combustion engines. In addition, FC systems can be build using modular, elementary “bricks” offering high levels of redundancy, they are silent and do not require intensive maintenance, since there are very few moving parts. Finally, the available fuel cell output powers and power density are rapidly improving, offering interesting perspectives for application on board of (smaller and/or slow sailing) vessels.

Till date, the limited maturity and production volume of fuel cell systems results in high costs, which has hindered adoption in shipping. However, with the prospected long term rise of fossil fuel prices and an increasing number of financial stimuli for adopting alternative fuels and technical solutions, fuel cells on board of ships (e.g. Proton Exchange Membrane (PEM), High Temperature PEM (HT-PEM) and Solid Oxide Fuel Cell (SOFC) come into the picture. The opportunities and challenges for the use of fuel cells in maritime shipping have been highlighted in a study carried out in 2017 by the European Maritime Safety Agency (EMSA)[2]. Multiple pilot projects have been executed with hydrogen as a fuel for PEM fuel cells (e.g. ZEMSHIP, Nemo H_2). Next to this, several projects with HT-PEM fuel cells are developed with methanol and/or hydrogen as a fuel (e.g. Pa-X-ell, RiverCell).

The wide variety of possible alternative fuel and fuel cell type combinations demonstrate that fuel cell systems allow for a certain degree of flexibility. Depending on the requirements and the constrains of a given ship type, some of these combinations may be more interesting than others from a business case perspective. Hydrogen is a common fuel for fuel cell systems, but other alternatives decrease the volume required on board for storage due to their higher energy density. In addition, methanol and ammonia are, for instance, easier to handle than hydrogen with regard to typical storage temperatures and/or pressures. Although some of these fuels can be used directly in SOFCs, they may also be processed to a hydrogen rich mixture prior to the fuel cell. For new vessels with stringent emission limits, renewable fuels seem to offer excellent opportunities to lower both

GHG emissions like CO_2 as well as hazardous air pollutants (PM, NO_X and SO_X). Moreover, opportunities seem to arise for the conversion of existing vessels as well.

This project aims to provide better insight in the technical and economic feasibility of different fuel cell configurations on board different ship types in combination with various alternative fuels. The applicability of these configurations on board of ships is studied with regard to technology readiness levels (TRLs), emissions and global fuel availability. At present, the following vessel types come into view: service vessels in ports, canal boats, smaller work vessels, pilot vessels, survey vessels, smaller inland vessels, and similar.

In prospected follow up projects, consortia of maritime companies and organisations may test selected system configurations of renewable fuels and fuel cells on ships. This will lead to demonstrators on board new build and/or existing vessels.

This project will be executed using the following work packages:

1. Determination of the state of the art with regard to fuel cell technology for maritime application in combination with (renewable) alternative fuels;
2. Review of potential and possible business cases for end users;
3. Identification of problems with regard to fuel composition and fuel storage (possibly reform technology), fuel cell technology, system configuration and performances;
4. Possible challenges and opportunities, inventory of technology supply and knowledge of the Dutch maritime industry and research organisations;
5. Development of follow up projects for vessels sailing on fuels cell and using alternative (renewable) fuels.

2. State of the art

2.1 Technology state of the art fuel cell

Fuel cells are classified primarily by the type of electrolyte material that separates the fuel and air electrode. These materials also determine the mobile ion, electro-chemical reactions and the temperature ranges at which these occur. In addition, it dictates the nature of the catalyst as well as the type and required purity of the fuel. Each fuel cell type comes with its own set of characteristics and specific needs in terms of process control, which in turn determine the degree of complexity of its Balance-of-Plant (BoP), i.e. the auxiliary components in the system. All of the above factors influence heavily the applicability of each type of fuel cells in maritime applications. In recently conducted studies, the technologies identified as the most promising are LT- and HT-PEMFC and SOFC, for which reason they will be introduced in more detail[2,3,4].

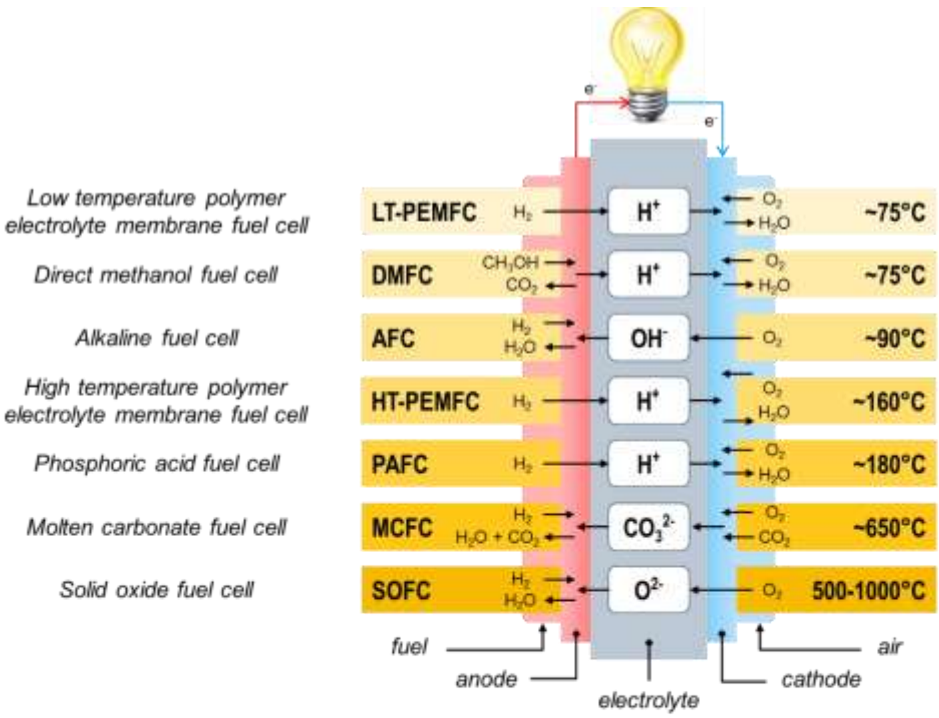

Figure 1. *Different fuel cell types and their mobile ions and respective operating temperature*.

2.1.1 Low temperature Polymer Electrolyte Membrane Fuel Cells

The LT-PEMFC is currently the most widely used fuel cell technology and has been used successfully both in marine and other heavy duty applications. They employ solid polymer-acid membranes (mostly based on Perfluorosulfonic acid (PFSA)) as electrolyte and porous carbon electrodes that also act as support for a platinum-based catalysts. This specific type of polymer electrolyte membrane has to stay hydrated for the membrane to conduct mobile protons, resulting in operating temperatures below 100°C. The redox reaction within PEMFCs transforms the energy stored in hydrogen into electricity, heat and water using an oxidizing agent, most commonly ambient air. Electrons liberated during the reaction cannot travel through the electrolyte and are redirected via an external load, thus producing an electric current for useful work. This process is schematically shown on the top of Figure 1. This energy conversion process occurs at relatively low temperatures, ranging from roughly

65 to 85°C, reaching peak efficiencies of around 50-60%. Maintaining this temperature range is mandatory, given that liquid water contained in the membrane acts as the hydrogen H^+ ion transporting medium.

LT-PEMFCs offer a wide range of attractive characteristics. Low temperature operation induces less stringent material requirements and offers flexible operation, that is tolerance for load cycling, resulting in good transient performance and load following capabilities. The use of a solid yet flexible electrolyte that offers chemical, thermal and mechanical stability up to 100°C, means that electrolyte management problems are significantly reduced compared to the liquid electrolytes used in some of the other fuel cell types (AFC, PAFC, MCFC). Low-temperature operation also allows for a short warm-up time, allowing cold starts in seconds. Moreover, degradation processes are slowed down in comparison to high temperature fuel cells, inducing less wear on system components leading to longer operational lifetimes. High achievable current densities and small physical size also result in high power-to-weight ratios, making LT-PEMFCs a suitable technology for weight- and volume-sensitive applications such as transport. Given the low temperature of operation, main safety aspects are related to the use and storage of hydrogen on a vessel.

One of the main disadvantages of operating at low temperature is the relatively slow rate at which the chemical reactions occur, which induces the need for a catalyst from the noble metal family (typically platinum) and, subsequently, adds to system cost. Furthermore, at this range of operating temperatures, the platinum catalyst is extremely sensitive to fuel impurities, in particular carbon monoxide (CO). CO has a strong surface adsorption, which deactivates the catalyst and blocks hydrogen access. For this reason, very high purity hydrogen (> 99.99%) is required to maintain satisfactory performance.

The second significant drawback is water management. On one hand, the polymer membranes needs high liquid water content to achieve low resistance to the flow of H^+ ions, but at the same time, the pores of the electrodes have to remain dry to allow for a rapid diffusion of reactant gases. Because the delicate balance between water generated, transported and removed inside the fuel cell, LT-PEMFCs have typically a complex water management system. This drawback is set to be rapidly alleviated as state-of-the-art fuel cell solutions contain advanced gas diffusion layers that facilitate the extraction of liquid water from reaction sites (e.g. the Toyota fuel cell system used in the Mirai[5]). This allows to simplify system management and its structure by removing the external humidifier. Finally, the low operating temperature and the resulting low quality heat produced mean that heat recovery is considered to provide very limited benefits.

Even though perfectly capable of load following, the carbon support and platinum catalyst inside LT-PEMFCs have been proven to degrade at a much faster rate under load cycling conditions. Because of this, it is highly recommended to operate at steady-state as much as possible and delegate rapidly-varying load demands to fast-response energy storage devices such as batteries or supercapacitors.

Although lifetime is often seen as a limitation of FC systems, this is actually not the case. Stationary LT-PEM have already proven more than 65000 h of operation[6]. Heavy-duty mobility grade systems installed onboard some European buses demonstrated successfully 35000 h of operation[7], what translates to over 8 years of service, with an ultimate target of 50000 h[8]. As with many industrial endeavours, the economy of scale applies to fuel cells as well. Nowadays, the total production volume of PEMFCs is relatively low, resulting in costs per kW of LT-PEM system ranging anywhere from 1000 to 2500 €/kW_e (heavy-duty grade). Projected increase in production numbers and manufacturing scale-up lead to an estimated fuel cell price drop to below 600 €/kW_e on the mid-term (2025-30)[9], with an ultimate objective of ~50 €/kW_e for light-duty grade systems and ~80€/kW_e for heavy-duty (2050)[10].

2.1.2 High temperature Polymer Electrolyte Membrane Fuel Cells

In response to some of the technological limitations of LT-PEMFCs, a variant capable of working at higher temperatures has been developed. In HT-PEMFCs, the water-based PFSA membrane is replaced by another proton transport assisting solvent that possesses a higher boiling point. One of the most popular electrolytes currently in use is a polybenzimidazole (PBI) polymer matrix doped with phosphoric acid (H_3PO_4). This technology offers good protonic conductivity and catalytic activity in the range of 140-180°C, while demonstrating mechanical, chemical and thermal stabilities beyond the 200°C threshold.

The advantages of working at elevated temperatures are numerous, including higher achievable performance due to increased reaction kinetics and lower diffusion losses (as water vapour exists only in its gaseous state) and increased tolerance to impurities, like CO or sulphur compounds. Since the adsorption of CO is reduced at higher temperatures, the tolerance to it is raised to ~3% of content in the fuel stream, allowing the use of lower purity hydrogen originating from, for instance, the steam reforming process. There are, for example, HT-PEMFC systems available on the market with integrated fuel reformers for natural gas and methanol. This does, however, imply that some of the fuel need to be bled and the fuel utilisation is limited to <100% and consequently the efficiency of such systems is typically lower than for pure hydrogen.

Alongside the fuel cell itself, higher operating temperatures can have a positive impact on the BoP components. The increased temperature gradient between the system and the ambient air allows for a smaller cooling system, while enabling the recovery of excess high quality heat for further use. This can improve the overall efficiency of the system, leading to applications like Combined Heat and Power (CHP) units. Moreover, the absence of liquid water in the fuel cell eliminates the need for a water management system.

Unfortunately, working at this temperature range also comes at a cost as the heating and cooling management systems start to play a crucial role. HT-PEMFCs need to be pre-heated by external means to (typically) at least 120°C before power can be generated. This is mainly due to the fact that the proton-carrying H_3PO_4 is extremely hydrophilic and binds effortlessly with liquid water molecules. This can result in rapid removal of the electrolyte from the PBI polymer matrix, substantially decreasing fuel cell performance and lifetime. For this reason, the introduction of liquid water should be avoided at all costs and as a consequence, cold start is impossible. Start-up and shut-down sequences become longer and more complex when compared to LT-PEMFCs.

Long term operation at high temperatures and dry conditions accelerate membrane degradation. Also, during transient operation, changing operating conditions (load, temperature) may lead to increased formation of water, increased thermal and mechanical stresses and voltage cycling that accelerates carbon support and catalyst degradation. Current lifetime of HT-PEMFCs are still limited to around 5000 hours, which limits their commercial success[11]. However, lab tests suggest that lifetime in excess of 20000 can be achieved in principle[12]. The higher system complexity and number of components result in a cost level, expected to be around three times of their low temperature counterpart running on pure hydrogen[13].

2.1.3 Solid Oxide Fuel Cells

Solid oxide fuel cells (SOFCs) rely on a ceramic membrane material that allows diffusion of oxide ions at relatively high temperatures. Functional temperatures vary from 500 to 1000°C, depending on the cell design and the electrolyte material of choice. Designs vary from thick electrolyte supported cells to functional layers supported on a porous electrode or metal support.

The high operating temperature enables the use of non-noble catalysts in the electrodes, such as nickel. In addition, SOFCs have higher tolerance for fuel impurities, and carbon monoxide is effectively a fuel. Therefore, SOFCs can be fuelled with (reformed) hydrocarbons as well. Light hydrocarbons, such as methane, can even be reformed internally on the SOFC anode. Likewise, ammonia can be cracked internally and, therefore, directly used as a fuel.

SOFCs are, for example, used for (micro-)CHP generation from natural gas, taking advantage of the high temperature waste heat produced. Products with peak electrical efficiencies up to 60% have been on the market for several years in Japan and more recently in Europe. Today, SOFC are applied in distributed power generation as well, most notably to provide power at businesses and datacentres in remote locations or locations with no access to a reliable electricity grid. These systems are designed to use natural gas and have a peak net electric efficiencies up to 65%.

SOFC technology can also be applied in a combined cycle configuration with a heat cycle, for which net electrical efficiencies over 70% are projected. SOFC-gas turbine combined cycles have been developed by Siemens-Westinghouse, Rolls-Royce, LG and Mitsubishi Hitachi. The latter started production of a 250 kW_e system with a peak efficiency over 54%, named *MEGAMIE*. General Electric has announced the development of a SOFC hybrid with one of their Jenbacher gas engines, projected to achieve efficiencies over 65%.

Compared to other fuel cell systems, SOFCs typically have a large amount of auxiliary components, like heat exchangers, fuel reformers and combustors. In addition, a substantial amount of insulating material is used to minimise heat loss to the environment and maintain the high operating temperature of the stack. Although the power density can be high at cell level, relatively thick repeating units and the large balance of plant typically results in lower power densities than LT-PEMFC systems. In addition, the thermal mass of the system calls for adequate thermal management, resulting in time consuming cold starts and sluggish load following.

Being targeted for stationary applications, SOFCs are typically designed to achieve relatively long life times. Stack lifetimes in products vary from 20 to 40 thousand hours today, while future generations are expected to achieve lifetimes up to 90 thousand hours[14]. The total production volume of SOFCs is relatively low today. Therefore, manufacturing costs are relatively high, typically over 3500 $/$kW_e$ (approx. 2900 €/kW_e in January 2021) without mark-up and sales[15]. Estimated cost for large-scale manufacturing varies from 500 to 2000 $/$kW_e$ (approx. 400 – 1650 €/kW_e) depending on the system power rating[16].

Figure 2. SOFC power systems sold by Bloom Energy.

2.1.4 Other types of fuel cells

The viability of using a specific fuel cell technology in maritime applications depends largely on its operational characteristics and ease of implementation. Because of the broad spectrum of interesting attributes offered by LT- and HT-PEMFCs and SOFCs, these types are considered a viable choice for maritime use[2]. For completions, this section describes other fuel cell types which are less likely to be applied in ships, either due to severe intolerance to impurities, high cost, low power density, low system efficiencies, liquid electrolyte management and resulting high system complexity and maintenance requirements.

Alkaline Fuel Cell (AFC)

AFCs consist of an alkaline solution electrolyte, typically potassium hydroxide (KOH), where hydroxyl OH^- ions are transported from the silver-based cathode to the nickel-based anode. AFCs have a moderate efficiency of around 50-60%, employ low-cost catalysts and readily available electrolytes, which renders them a relatively low-cost system.

The fuel cell uses hydrogen and oxygen as reactant gases and operates between ambient temperature and 90°C, which ensures that the requirements for the material used are less stringent and reduce cost. The biggest drawback of AFCs is their high intolerance to CO_2, which will react with the alkaline electrolyte, reducing process efficiency and eventually leading to precipitation and blocking of the cell by potassium carbonate. For this reason, pure oxygen and pure hydrogen gases need to be delivered for it to function in an optimal range over a prolonged period of time, or potassium carbonate has to be removed and the electrolyte replenished. This implies that AFC systems typically use a scrubber to remove CO_2 from the cathode air. However, the AFC membrane has a high tolerance for ammonia, which is an advantage compared to the acidic proton conducting membranes employed in some fuel cell types if ammonia is considered as a fuel.

Phosphoric Acid Fuel Cell (PAFC)

PAFC have an electrolyte consisting of silicon carbide matrix saturated with liquid phosphoric acid and carbon electrodes that support a platinum catalyst. This is the precursor technology that lead to the development of HT-PEMFC, for which reason they share many of the same benefits and shortcomings. The higher operating temperature from 140 to 200°C reduces the required platinum loading and increases CO tolerance, but also offers to use the excess high quality heat, increasing the overall efficiency of the fuel cell from around 40% up to 80%. Reachable current densities are relatively low which translates into low power densities and result in large and heavy systems. Higher temperature operation results in slower start up times and accelerated component ageing.

Direct Methanol Fuel Cell (DMFC)

DCFCs employ a polymer membrane electrolyte, similarly to PEMFCs, but to generate electricity they use a 3% methanol (CH_3OH) in water solution, without prior reforming to hydrogen. The ability to do so is granted by electrodes containing a platinum-ruthenium catalyst. The DMFC normally operates between 50-120°C. Increasing operating temperature and pressure can improve cell efficiency, but will also cause higher overall losses, leading to losing the benefit.

DMFCs are good for delivering small power outputs, typically of up to 5 kW, over prolonged periods of time. The methanol is as fuel with high energy density, that is easy to handle and store compared with hydrogen but its use during the oxidation at the anode leads to CO_2 production. The efficiency of a DMFC is low, around 20 % with a major challenge being methanol crossover from the anode to the cathode where it reacts directly with oxygen. This can lead to severe reductions of cell efficiency.

Molten Carbonate Fuel Cell (MCFC)

The MCFC is a high temperature fuel cell operating between 600-700°C. The electrolyte is a molten carbonate salt composed of sodium and potassium carbonate. Due to increased reaction kinetics, noble-metal catalyst can be replaced with low-cost alternatives such as a nickel-based alloy at the anode and a nickel-based oxide interlaced with lithium at the cathode. CO_2 needs to be supplied at the cathode, since carbonate (CO_3^{2-}) is the mobile ion. This is usually obtained from the flue gases, which implies that hydrocarbon fuels are to be used.

The high temperature makes the MCFC flexible towards the choice of fuel, without the use of a reforming unit. Here, LNG, flue gases from coal and hydrogen can be used as fuel. The electrical efficiency of a MCFC is around 50%, but the total system efficiency can reach as high as 85% when other reaction products are used in a heat recovery system or a turbine (flue gases can be used in an afterburner).

The high temperature makes MCFC suitable for heat recovery systems, but also makes it vulnerable to negative cycling effects like corrosion and cracking of components. The fuel cell presents a slow start-up, and is less flexible towards changing load demands than low temperature fuel cells. Also, using hydrocarbons leads to CO_2 emissions and heat and energy recovery systems have the potential for some NO_X emissions. MCFCs are commercially available, but still struggle with high cost, limited life time and low power density.

2.1.5 Summary of promising technology characteristics

Table 1 summarises important parameters and operating characteristics of the most promising fuel cell types for maritime application: the LT- and HT-PEMFC and the SOFC.

Table 1. Summary of SOFC, LT- and HT-PEMFC characteristics.

	LT-PEMFC	HT-PEMFC	SOFC
Operating temperature (°C)	65-85	140-180	500-1000
Electrical efficiency (% LHV)	40-60	40-50	50-65
Fuel requirements	99.99% H_2	CO < 3%	S < 20 ppm
Gravimetric power density (W/kg)	125-750	25-150	8-80
Volumetric power density (W/L)	50-400	10-100	4-32
Stack life time (kh)	5-35	5-20	20-90
System life time	≥ 10 years with stack replacement		
Cold start-up time	<10 seconds	10-60 minutes	>30 minutes
Load transients (0 to 100%)	seconds	<5 minutes	<15 minutes
Current capital cost ($/kW)	1000-2500	3000-5000	3500-15000
Future capital cost ($/kW)	60-600	150-1500	500-2000
Maritime TRL (2020)	6-7	5-6	4-5
Cooling medium	Liquid	Liquid	Air

In addition to the information in the table above, *Figure 3* shows how the typical operating characteristics of fuel cell differ from traditional internal combustion engines[17]. Fuel cells typically have a high efficiency at a relatively low load, where the electrochemical losses in the stack are limited, while internal combustion engines are usually most efficient close to their rated operating point.

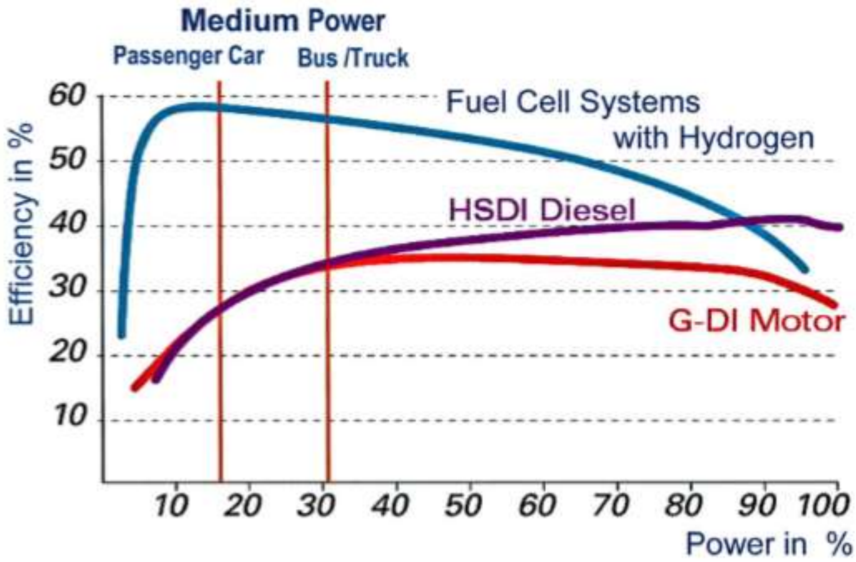

Figure 3. Comparison of efficiency versus power for fuel cell systems and internal combustion engines[17].

2.2 Potential fuels for shipping

2.2.1 MGO

Marine gasoil (MGO) comprises all the marine fuels that consist of distillates which are derived from crude oil often containing a blend of various distillates. MGO should not be confused with Marine Diesel Oil (MDO), which consists of a blend between distillates and heavy fuel oils. MGO is similar to diesel, although it has a higher density[18].

In contrast to heavy fuel oil (HFO), MGO does not require heated storage, due to the lower viscosity allowing the fuel to be pumped into the engine at approximately 20°C. Furthermore, marine gasoil is considered to be a clean fossil fuel especially when compared to HFO and MDO. Both GHG, particulate matter, and soot emissions of MGO are significantly lower compared to the more commonly used HFO[19]. MGO is more expensive than HFO. However, it is expected by industry insiders that the maritime industry will start using more MGO, mainly due to the optimization of production processes of refineries producing less residual fuel because of the falling price of HFO caused by stricter regulations[20]. Besides, McKinsey & Company expects that due to the IMO 2020 lower sulphur requirements shippers will switch to MGO[21].

2.2.2 Biodiesel

There are three general types of biodiesel. The first type of biofuel comprises of long-chain fatty acid methyl esters (FAMEs) derived either from biomass or biomass residues made into liquid fuel, through the process of esterification using methanol as a catalyst. Different raw materials may be used for the production of FAMEs, such as palm, coconut, rapeseed, soya, tallow or even cooking oils. Currently, the use of FAMEs is more widespread and is almost always blended and sold with mineral diesel fuel. Biodiesel is also produced by transesterification of vegetable oils, which in principle are suitable for the operation of diesel engines. However, energy content per kg is lower when compared to diesel. Other than that fuel properties as defined in European Norms (EU 14214) for FAME are similar to those of diesel fuels. In practice, the chemical composition of different FAMEs often vary significantly due to the wide variety of feedstocks from which the fuels are produced. In principle, FAMEs are suitable for diesel engines, although it is most often blended with other diesel fuels. FAMEs are known to reduce depreciation of the combustion system due to the higher lubricity, although esters are more polar, which attracts debris thereby polluting the fuel and plugging the filters. Therefore, FAME biodiesel in vehicle engines has a B7 blend wall meaning that diesel engines should be compatible with up to 7% biofuel contained in the fuel blend[22,23,24].

The second type is produced by hydro-treating vegetable oils or waste oil and fats (HVO). In this process, hydrogen is used to remove oxygen from the vegetable oil in order to create hydrocarbons. Although the technique is relatively new, its use has matured swiftly and is already a commercial option. In contrast to FAME, HVO is a hydrocarbon with an almost identical chemical composition to that of diesel fuels, making it compliant with diesel fuel specifications. HVO is a drop-in fuel and is functional equivalent to its fossil counterparts in the marine combustion engines, and thus fully functional within the existing infrastructure. HVO is very much like Distillate Marine Fuel (DMA) and therefore subject to the same regulations and norms. For this reason, HVO need not to be blended with MGO. Heating values are the highest of existing biofuels and HVO often requires less maintenance as the fuel has a low tendency to form deposits in the fuel injection system. Also, when compared to FAME, HVO has no issues operating in severe cold circumstances[25].

The newest type of biofuels are biomass-to-liquid or BtL fuels, in which lignocellulosic biomass is converted into synthetic liquid hydrocarbons. BtL has very good fuel characteristics and is low in sulphur and aromatic contents. Furthermore, like HVO it meets all the standards for normal diesel fuels. BtL is produced in two steps: First, synthesis gas is produced from biomass feedstock, after which the synthesis gas is converted into a liquid fuel. Conversion of the latter step is done by using a catalytic process known as the Fischer-Tropsch process. Currently BtL is still in the research and development phase and is yet to be commercialized[26].

Biodiesels (FAME, HVO and BtL) offer an alternative to the earlier discussed fossil fuels or can be added as a drop-in fuel. The main advantages of biodiesel are that the fuels are nontoxic, biodegradable, and renewable with the potential to reduce greenhouse gas emissions. However, traditional FAMEs are considered controversial as it often competes with the food industry. Besides, biodiesel is still more expensive when compared to fossil fuels[27].

2.2.3 LNG (grey and green)

Bio Liquefied Natural Gas (LNG) is liquified methane produced from biomass. It is an interesting fuel to support the transition from fossil fuels to renewables and to achieve the greenhouse gas emission reduction targets. Since it is chemically identical to fossil LNG and can benefit from the growing LNG infrastructure, there is increasing interest to use it in the shipping sector. LNG terminals in North West Europe currently can be found in Belgium, the Netherlands, UK, Denmark, Sweden and Norway.

Bio LNG can also be produced by upgrading biogas or by thermo-chemical conversion of lignocellulosic biomass, or other forms of biomass. The technical feasibility to produce bio-methane from biogas on a large scale has been demonstrated over the last decade. The production of bio-methane via thermo-chemical conversion is still at a demonstration stage with very limited commercial market penetration so far. Biomethane could be applied in exactly the same way as LNG and therefore not lead to any additional challenges. However, technological development is needed to produce the required amount of biogas to switch from LNG to bio LNG investments.

2.2.4 Methanol (grey and green)

Methanol is the simplest alcohol with the formula CH_3OH. It is a light, volatile, colourless, flammable liquid with a distinctive odour very similar to that of ethanol (drinking alcohol). However, unlike ethanol, methanol is toxic and unfit for consumption. Methanol is used as an antifreeze, solvent, fuel, and as a denaturant for ethanol. It is also used for producing biodiesel via transesterification reaction[28]. The global methanol production currently amounts to about 45 million metric tonnes per year. Methanol produced using natural gas as a feedstock has “Well-To-Tank” emissions similar to other fossil fuels such as LNG and MDO. Bio-methanol produced from second generation biomass such as waste wood has a much lower global warming potential than fossil fuels and is lower than ethanol by most production methods[29].

Black liquor from the pulp industry has been identified as an interesting feedstock for renewable energy. Black liquor is formed as pulpwood is mixed with chemicals (white liquor) to produce pulp as a pre stage to paper production. Black liquor can be gasified and used for methanol synthesis. The chemicals are recovered and reused. Black liquor is available in large quantities worldwide and offers a feasible way to produce methanol. Worldwide, about 400 million tonnes of pulp and paper products are produced every year. For the manufacturing of every tonne of pulp approximately seven tonnes of black liquor are produced[30]. In Iceland, renewable methanol is produced by combing hydrogen and CO_2. At present, about 200 thousand tonnes of bio-methanol are produced per year. Studies estimate that bio-methanol could reduce greenhouse gas emissions by 25-40% compared to methanol from fossil fuels if the entire life cycle is taken into account[31].

2.2.5. Ethanol (grey and green)

Ethanol is the principal alcohol found in beverages, produced by the fermentation of sugars and yeast, with the formula C_2H_5OH. It is a volatile, flammable, colourless liquid with a slight chemical odour. It is also used as an antiseptic, a solvent and a fuel. Bio-ethanol is currently the most widely used biofuel around the world. According to the Organisation for Economic Co-operation and Development (OECD), worldwide bio ethanol production amounted to about 120 million tons in 2018[32].

Current commercial bio-ethanol production is based on fermenting sugar or starch. For each kilogram of bio-ethanol about one kilogram of CO_2 is co-produced. Note that this CO_2 is biogenic, i.e. it stems from the biomass. Emission of this CO_2 to the atmosphere does not increase the amount of CO_2 in the atmosphere because it was captured from the atmosphere by growing the crop. Sustainability of bio ethanol is a challenge, because production relies heavily on sugar cane and corn production, which can be in conflict with the production of food. Ethanol can also be produced from lignocellulosic biomass, such as wood and grass. This could have some advantages for sustainability, costs (cheaper feedstock) and the yield per hectare, with trickle down effects on environmental aspects such as the overall greenhouse gas balance and biodiversity. The global production of lignocellulosic ethanol is still low, but the number of research and development initiatives is enormous and the first commercial demonstrations are coming online with significant volume production expected in the coming years. As of 2012, about 100 pilot and demonstration plants were listed based on lignocellulosic biomass.

Ethanol has a few technical and logistical drawbacks. It increases vapour pressure, which means that the gasoline in which it is blended, must be adapted on beforehand. Furthermore, it attracts water which means that extra measures must be taken in shipping and storage[33].

2.2.6 DME (grey and green)

Dimethyl ether (DME) is an organic compound with the formula CH_3OCH_3, simplified to C_2H_6O. The simplest ether, it is a colourless gas that is a useful precursor to other organic compounds and an aerosol propellant and is being studied as a future fuel option. DME can easily be used in diesel engines[34]. The global DME production currently is estimated at 15 million metric tonnes per year. Asia-Pacific is the largest market of DME, accounting for nearly 95.66% of the total market size in terms of value in 2014. DME produced from coal accounted for the largest market share among other raw materials such as methanol, natural gas, and bio-based feedstock in 2014. The European market by volume is comparatively mature. The major players of DME include Akzo Nobel N.V. and Royal Dutch Shell Plc. (the Netherlands), the Chemours Company (U.S.), China Energy Limited (Singapore), Mitsubishi Corporation (Japan), Ferrostal GmbH (Germany), Grillo Werke AG (Germany), Jiutai Energy Group (China), Oberon fuels (U.S.) and Zagros Petrochemical Company (Iran)[35].

The concept of converting black liquor (a by-product from pulp mills/paper mill residues) via syngas to Bio DME was demonstrated by the four-year Bio DME project funded by the EU's 7th Framework Programme, Swedish Energy Agency and participating companies. The world's first Bio DME production plant is at Smurfit Kappa paper mill in Piteå, Sweden. The pilot plant was inaugurated in 2010 with a capacity of about 4 tons per day using forest residues as feedstock. The estimated cost of the plant was EUR 14 million. Up until the summer of 2013 more than 500 tons of Bio DME had been produced and distributed to 10 heavy duty trucks, which in total accumulated more than 1 million km in commercial service[36]. The overall TRL level of Bio-DME is only 5, since Chemrec's pilot plant in Sweden has not expanded. Significant scale-up of at least 30 times will be required to reach full commercial scale[31].

2.2.7 Ammonia (grey and green)

Ammonia is a compound of nitrogen and hydrogen with the formula NH_3. It is a gas at standard room temperature and atmospheric pressure, but becomes a transportable liquid at moderate pressures and temperatures (10 bar/-33°C). Ammonia is a colourless gas with a pungent smell. It contributes significantly to the nutritional needs of terrestrial organisms by serving as a precursor to food and fertilizers. Ammonia, either directly or indirectly, is also a building block for the synthesis of many pharmaceutical products and is used in many commercial cleaning products. The global industrial production of ammonia in 2014 was 176 million tonnes.

Ammonia is sometimes called the "other hydrogen" due to its structure of three hydrogen molecules and one nitrogen molecule. The ability of ammonia gas to become a liquid at low pressures means that it is a good carrier of hydrogen and its liquid form is over 50% more energy dense per unit of volume than liquid hydrogen. Ammonia can thus be stored and distributed easier than elemental hydrogen. There are several fuel cells designed to use ammonia directly, what eliminates the need to separate the ammonia into its hydrogen and nitrogen elements before it is used in the fuel cell. These cells enable high efficiency conversion of ammonia to electric power. Ammonia combustion results in more engine power than any energy equivalent amount of hydrocarbons (gas, diesel), alcohols, or hydrogen. This is because burning NH_3 produces more moles of gaseous combustion products (N_2 and H_2O) than the other fuels (CO_2 and H_2O). Companies like Proton Ventures in the Netherlands offer modular NH_3 plants using water electrolysis and the Haber-Bosch process[37].

Traditionally, hydrogen for the Haber-Bosch-process comes from coal gasification or from natural gas. The American company NHThree recently developed a so-called Solid State Ammonia Synthesis (SSAS) and claims an 43% efficiency improvement compared to the Haber-Bosch process. Nitrogen can be taken easily from the air. The challenge for sustainable production of ammonia is in the sustainable production of hydrogen from electricity or another sustainable manner[38].

2.2.8. Hydrogen (grey and green)

Hydrogen with the formula H_2 is the smallest and lightest of all gas molecules, thus offering the best energy-to-weight ratio of all fuels. Hydrogen is commonly used to generate electric power using fuel cells but internal combustion engines and turbines can be used for combustion of hydrogen as well. Commercial engines for combustion of hydrogen are currently unavailable, and focus is primarily directed towards pilot projects including fuel cells, which have superior fuel to electricity conversion efficiency. However, as of today, hydrogen as a sustainable fuel is costly to produce, transport, and store. According to the International Energy Agency, in 2018, 74 million metric tons of H_2 were consumed globally[39].

There are two main pathways for producing hydrogen:

1. Electrolysis of water: Emissions associated with this are related only to power generation for the electricity. If renewable power (e.g. solar or wind) is available, hydrogen can be produced emission-free. However, overall emissions are significant for today's average European electricity grid mix.

2. Reforming of natural gas: Hydrogen is produced by the reaction of methane with steam, CO_2 is separated and (should be) used as a by-product. An advantage of this method is that the CO_2 can be captured at its source, by using a so-called Carbon Capture System (CCS).

The overall energy efficiency of producing hydrogen through electrolysis and using it in a fuel cell to produce electricity and power an electric motor appears to be substantially lower than the efficiency of charging a battery and using this electricity to power the same electric motor. Charging a battery is associated with small energy losses, in the order of between 5 and 10%. Producing hydrogen through electrolysis has an efficiency of approximately 65% - 80% (depending on the type of electrolyser), while additional losses of at least 30 – 35% should be expected from a well-performing fuel cell.

From an energy utilization point of view, the use of hydrogen cannot be recommended. However, hydrogen could be a viable solution in applications where vessels requiring high autonomy (long cruising range without refuelling) does not allow for battery charging and/or the use of existing battery technologies due to weight limitations, provided that the size of the hydrogen tanks is not prohibitive. In addition, an energy infrastructure based on liquid and gaseous fuels can complement the electricity grid in terms of redundancy, cost and long term storage.

Special consideration has to be given to storage of hydrogen on board ships to ensure safe operations. Even though compressed hydrogen has a high gravimetric energy density (over two times higher than diesel), it also has a very low energy density by volume, requiring six to seven times more storage space than HFO. It is estimated that the tank size must be 10-15 times larger than required for HFO, depending on the storage pressure.

Liquefied hydrogen requires cryogenic storage at very low temperatures (-253°C), associated with large energy losses and very well insulated fuel tanks. Liquid hydrogen storage and transport on board a maritime vessel is being actively investigated. One such example is the Hydrogen Energy Supply Chain (HESC) demonstrator project. It is currently in its pilot phase, with first operations to be carried out in 2020, followed by technical reviews and commercial operations potential analysis in the years to come.

The hydrogen storage tanks can additionally result in loss of cargo space due to their size and shape. These increased costs of the fuel and the current limited gains in CO_2 emissions, combined with challenges regarding storage of hydrogen, safety, and the cost of fuel cells, imply that the uptake of hydrogen and fuel cells in ship propulsion may still be limited in the near future.

2.3 Fuel preparation

Hydrogen can be readily used in almost any type of fuel cell. The kinetics of electrochemical hydrogen oxidation reaction are fast, especially on noble metal catalysts like platinum. Other fuels, like hydrocarbons or ammonia, may need treatment prior to the fuel cell. Hydrocarbon fuels need to be reformed to a hydrogen-rich mixture of hydrogen and carbon monoxide (syngas), while ammonia can be cracked to form a mixture of hydrogen and nitrogen. Other fuel preparation steps include, among others, heating, evaporation, filtering, cleaning, purification and humidification.

2.3.1 Reforming

Reforming is used to convert organic compounds consisting of carbon, hydrogen and oxygen, such as hydrocarbons, alcohols and ethers into so-called syngas, a mixture of carbon monoxide and hydrogen. There are different types of reforming:

- Steam reforming: an endothermic reaction with steam which results in the highest hydrogen yield;
- Dry reforming: an endothermic reaction with carbon dioxide;
- Catalytic partial oxidation: an exothermic reaction with oxygen, usually air;
- Autothermal reforming: a combination of catalytic partial oxidation and steam reforming resulting in a isothermal process.

Reforming temperatures vary depending on the reforming agent, catalyst material and fuel type. Methanol can be reformed at temperatures as low as 200°C, while the stable methane molecule requires reforming at temperatures typically ranging from 700 to 900°C.

Reforming is very cost-effective on industrial scale, as most hydrogen is produced through steam reforming of natural gas. Smaller reforming systems have been developed for industrial gas supply and even micro combined heat and power solutions based on fuel cells. It is expected that the fuel reformer will be integrated with the BoP of the fuel cell system. A study on HT-PEMFC systems estimates the cost of the reformer to range from 180 $/kW (~ 150 €/kW), for 100 kW units manufactured at large scale to 650 $/kW (~ 540 €/kW) for smaller systems and low production volumes[13].

2.3.2 Cracking

Thermal cracking is a process commonly used in petrochemistry to break long, complex organic molecules down to light and simple ones. These molecules can be cracked further, forming (hydro)carbons and hydrogen. Thermal cracking does not require a reforming agent, such as steam or air, but the formation of solid carbon is typically problematic for fuel cell systems as it blocks porous catalysts. However, the process is useful when converting ammonia to a mixture of hydrogen and nitrogen. This reaction takes place at temperatures ranging from 650 to 1000°C, depending on the catalyst, and can proceed internally on the nickel catalyst in high temperature SOFCs. Ammonia cracking for hydrogen generation is not widely used today, hence cost estimations are difficult. However, the process does not require a reforming agent, simplifying the reactor. In addition, no noble catalyst is required at high temperatures and the reaction is less endothermic than reforming. Therefore, a lower cost is expected compared to a reformer with the same power rating.

2.3.3 Purification

SOFCs can readily work with a syngas mixture obtained from reforming or cracking. However, the allowable carbon monoxide concentration varies from less than 3% for HT-PEMFCs to less than 0.2 ppm for LT-PEMFCs. There are several methods to reduce the carbon monoxide content in a syngas mixture to acceptable values, including water gas shift (WGS), preferential oxidation (PrOx), selective methanation (SMET), pressure swing adsorption (PSA) and selective membranes.

In a WGS reactor, carbon monoxide reacts with steam to form hydrogen and carbon dioxide. The reaction takes place at temperatures between 200 and 400°C. Higher temperatures reduce the size of the reactor but favour higher carbon monoxide concentrations. The remaining carbon monoxide can be converted to carbon dioxide by preferential oxidation, but a part of the hydrogen will be oxidised in the process as well. Alternatively, carbon monoxide can react with hydrogen to form methane in a selective methanation reactor. This option is sometimes preferred when the tail gas is further used, for example to fuel a burner.

Carbon dioxide and methane can affect the performance of LT-PEMFCs negatively, and further purification may be required. Pressure Swing Adsorption (PSA) is used in industrial processes to purify hydrogen to the level required for LT-PEMFCs. PSA is cost effective for relatively high hydrogen concentrations and large scale. However, the high footprint and power consumption for small scale systems may result in prices >3 $/kg of H_2[40]. In addition, hydrogen recovery from PSA is limited in practice and 15 to 25% of the hydrogen is lost in the tail gas. Selective membranes can achieve similar purities with less power input and a lower footprint, but being made from precious materials like palladium and are relatively expensive as well.

2.3.4 Heating and evaporation

Fuel and air need to be supplied at the right conditions to maximise fuel cell power and efficiency. Most fuel cells operate with gaseous fuels, which implies that liquid fuels, such as methanol, need to be evaporated in the system. The temperature of the fuel that enters the fuel cell stack is important for high temperature fuel cells, since a large difference with the operating temperature can result in reduced power and thermal shock. This is particularly important for SOFCs, which employ a brittle ceramic membrane material. Evaporation of fuel and air can typically done with hot exhaust gases from the fuel cell stack or, if present, the catalytic afterburner. The cost for heating and evaporation equipment are normally included in the fuel cell system costs.

2.3.5 Filtering and cleaning

Particulates in air and fuel can damage fuel cell electrodes and catalysts used in fuel reactors by blocking pores and access to reaction sites. Similarly, contaminants in the fuel can damage fuel cell electrodes or react with stack components. For example, ammonia reacts with the membranes employed in low temperature PEMFCs, and sulphur with the ceramic membranes of SOFCs.

Particulate filters are typically used in the air supply systems of fuel cells. For maritime fuel cells, the cathode air filter system should be adequately removing salt-water droplets as well as particulates. Little to no fuel treatment will be required if hydrogen within manufacturer specification is used. If not, further fuel cleaning is required. For example, adsorption can be used to reduce the sulphur content of LNG to acceptable levels, varying from a few ppb for PEMFCs to a few ppm for SOFCs.

Some of the filtering and cleaning is an integral part of the fuel cell system and therefore included in the system cost. SOFCs are, for example, usually equipped with an absorber for sulphur. Other equipment may need to be installed separately, such as air filters. The air and fuel quality requirements are usually clearly stated by the fuel cell system manufacturer. Occasional replacement of the sorbent beds and filters will be required and adds to the operational expenses.

2.3.6 Inlet gas humidification

Water management is of key importance to LT-PEMFCs, who's proton conductivity largely depends on proper membrane humidification. On the other hand, excess water has to be removed from the cathode side to prevent it from blocking the porous electrodes (flooding). In addition, swelling and shrinking of the membrane due to varying membrane humidification can cause mechanical strain to the fuel cell stack, potentially leading to material fatigue and damage.

As was highlighted in fuel cell state of the art (in Section 2), incorrect water mass balance inside LT-PEMFCs is becoming less of an issue as many manufacturers are developing advanced cell and stack designs to facilitate proper humidification of the membrane, while effectively removing the liquid water product from the cathode. This is referred to as internal humidification. Nonetheless, water exchange membranes are still used to humidify the incoming fuel and air, referred to as external humidification. External humidification is sometimes integrated in the stack design. Humidification is usually an integral part of the fuel cell system.

2.3.7 Overview

Figure 4 gives an overview of different fuel processing steps and their temperature, obtained from van Biert et al.[3]. The overview reveals the complexity of using non-hydrogen fuels with LT-PEMFCs, while reforming processes can be beautifully integrated with high temperature fuel cells as they require high temperature steam and heat.

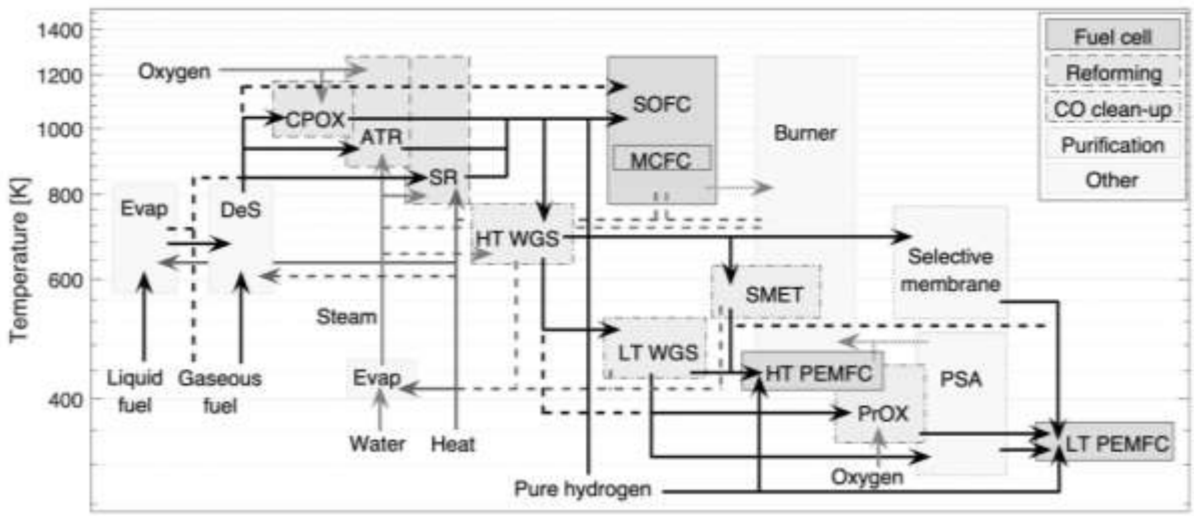

Figure 4. Overview of fuel processing steps and temperature ranges for different fuel cell types[3].

2.4 Definition of possible user/vessel groups

The size of currently available fuel cell modules is typically still limited to the kW power level. Scaling of the fuel cells to larger stacks and modules with a lower footprint is an important challenge, as well as behaviour in part-load, load transient capabilities and lifetime. Therefore, the initial focus will be on smaller vessels up to 1000 kW in required propulsion power, or larger vessels where fuel cells can contribute to the auxiliary power.

The power rating of LT-PEMFC modules typically varies from around 50 to 200 kW_e. Some of these products have a type approval for maritime application. Larger systems, such as the 3.2 MW system ordered for a cruise vessel of Havila, usually consist of a number of these smaller building blocks. HT-PEMFCs on the market today are typically around 30 kW_e, which are in turn build from 5 kW_e units. The power rating of heavy-duty SOFC systems varies from about 20 up to 300 kW_e. These systems are in turn assembled from modules ranging from about 5 up to 100 kW_e. The 2 MW_e system to be supplied for the ShipFC project is to be built from 100 kW units developed in another project.

In 2017, the applicability of alternative power plant solutions for maritime vessels has been evaluated in a report published by the Sandia National Laboratories[41]. The conventional fossil fuel-based systems of 14 different vessels with various routes, ranging from small passenger vessels to the largest cargo ships, were substituted by three solutions: pure battery electric, fuel cell electric with gaseous hydrogen storage and fuel cell electric with liquid hydrogen storage. Results of this analysis have shown that existing zero emission powertrains (2017 numbers) can meet the propulsion power and energy storage requirements for the large majority of studied vessels, at the same time respecting the mass and volume envelopes of the current fossil fuel-based solution. Hydrogen fuel cells with liquid hydrogen storage proved to offer the highest autonomy, while battery systems showed an advantage for high power, short duration missions.

Given the large power requirements of vessels, fuel cell system modularity and scaling effects are key. For now, increasing the installed fuel cell power implies the installation of a larger number of low power units. However, this may increase the total size of the power generation system due to additional piping and safety zone requirements. Larger systems with higher powers can be constructed as well, but need to be certified separately. In addition, it is not yet clear how this will affect power density, transient behaviour and system lifetime.

Early adopters for fuel cell technology on ships are therefore expected to have an installed power up to around 1 MW. However, fuel cells can also deliver a part of the (auxiliary) power on vessels with larger power requirements. Therefore, target vessel types include:

- Governmental vessels (survey vessels, inspection vessels etc.);
- Harbour support vessels (tugs, line handlers, patrol vessels, pilot etc.);
- Inland passenger vessels and ferries;
- Inland cargo vessels;
- Small work vessels operating in inland or coastal waters;
- Auxiliary power on cruise vessels.

3. Potential business cases

Based on the information gathered in the previous work packages, a round table with representatives of MKC, TNO and TU Delft was organised in June 2020 to discuss the most promising combinations of fuels cell, fuel and vessel type as well as the potential business cases. In close co-operation with Netherlands Maritime Land a FCMAR webinar was hosted on 17 September 2020 with a maximum participation of twenty people. The webinar was attended by various representative from port authorities, the Ministry of Infrastructure & Water management, the Ministry of Defence, the Ministry of Economic Affairs and Climate Policy, research institutes, universities, industry and new energy consultants. A full list of representatives and the minutes of the meeting are provided in Appendix 1. Appendix 2 includes the presentation given on the FCMAR webinar including a comprehensive list of pilot projects.

In general, it can be concluded that interest for fuel cell applications exists, especially within governmental institutions and especially the operational departments. This applies for the Ministry of Infrastructure and Water management and their operational department "Rijksrederij", the Ministry of Defence and their design department DMO as well as the Port of Amsterdam. There seems to be a growing interest on the current state of the art of fuel cell technology and the applicability of the technology especially for maritime (semi-) governmental applications.

Explicit business cases are not yet in view, when costs of the technology and integration with ships systems are compared to the current state of the art combustion engine technology. The typical capital cost for conventional marine internal combustion engines varies from as little as 250 USD/kW for large two stroke diesel engines (50 MW scale) to 1000 USD/kW for small four stroke dual fuel engines (1 MW scale)[42]. Dual fuel engines for hydrogen are expected to enter the market with up to 50% added cost (<1500 USD/kW). This would make the fuel cell option competitive, but the mostly mechanical propulsion systems are relatively inexpensive compared to the electric drive systems required when fuel cell systems are used.

Regarding propulsion systems based on fuel cells, Taljegard et. al.[43] states that the costs for marine fuel cells range anywhere between 100 to 1500 USD/kW, excluding the costs associated with fuel storage and piping. As discussed in Chapter 2, the exact cost highly dependent on the fuel cell type, lifetime and production volume, but this figure is still more or less correct. Based upon these references a best estimate for the a fuel system including storage, piping and additional investments in the power and propulsion system may range anywhere between €2000 and €3000/kW. The current costs for fuel cells are substantially higher than traditional internal combustion engines, but with regard to long term investment decisions, fuel cells can be an interesting choice.

As of today, the use of PEM fuel cells in combination with hydrogen has the highest maturity level and is the most promising choice for organisations that want to invest in ships with fuel cell technology in the near future. In fact, several demonstrator projects have already taken place in The Netherlands and in Europe with regard to the use of PEM fuel cells and hydrogen. In most cases, relatively small vessels were used for demonstrator purposes as they provide an adequate first exploratory step.

SOFC with LNG (or MeOH and NH_3) are also currently developed for maritime applications, but have a lower TRL in comparison to PEM fuel cells. Furthermore, it is important to note that draft regulations for fuel cells are still immature, in which relevant definitions, goals and functional requirements remain subject to discussion. Several issues with regard to system integration, durability, efficiency and safety of fuel cells require further research and development.

4. Challenges and opportunities

4.1 Potential challenges

4.1.1 Technical challenges

Despite rapid developments in the automotive applications and trains, overall, fuel cell technology is mostly not yet on par with state of the art marine diesel engines regarding:

- Power density and specific power
- Load transient capabilities
- Life time

Power density and specific power

The LT-PEMFC has best performance regarding power density and specific power. Marine fuel cell systems are available with a specific power of 230 W/kg and a power density of 100 W/L respectively (Ballard FCwave™). In comparison, a 400 kW_e Caterpillar marine gas generator set (CG132B-8) achieves 80 W/kg and 40 W/L and is thus larger, heavier and has a higher specific fuel consumption. However, additional electrical conversion and electric motors will be required when fuel cells are used for electric propulsion, whereas the generator of the Caterpillar engine can be omitted for mechanical propulsion.

HT-PEMFCs on the market have lower power densities compared to their low temperature counterpart, mostly due to the smaller unit power and the inclusion of fuel reformers and heat exchangers. For example the 5 kW methanol-fuelled Serenergy HT-PEMFC module has a specific power and power density of roughly 80 W/kg and 60 W/L respectively, similar to a small marine gas generator set[44].

Today's SOFC technology has very low specific power and power density, with about 20 W/kg and 10 W/L for a 300 kW_e Bloom Energy Server, thus four times larger and heavier compared to a the Caterpillar gas generator set with a similar power rating. Despite its low fuel consumption, this poses a real challenge when integrating these systems on ships.

Load transients

The marine environment can be very demanding when it comes to transient load conditions. Heavy sea states cause large fluctuations on propeller loads, and fuel cells need to be able to deal with those in order to ensure the safety of the vessel, her crew and her environment. In addition, specialty vessels like naval ships, high-speed ferries, work boats and fishing vessels can have highly fluctuating auxiliary loads.

Similar to the previous section, LT-PEMFCs have the best transient capabilities, typically completing a ramp to full power within seconds, while HT-PEMFCs and SOFCs rather need minutes to reach a new stable operating point. Although the electrochemical reactions respond quickly to load changes, the balance of plant components need more time to adjust fuel, air and coolant flows. Large thermal masses induce long settling times in high temperature fuel cell systems.

Load transients in fuel cell system are ultimately restricted to ensure that the balance of plant has time to respond and prevent deteriorating conditions in the system. Such conditions may include local overheating, thermal stresses, fuel or oxidant starvation, catalyst and catalyst support degradation, drying or flooding and pressure peaks. Robust system design and sophisticated control strategies can improve transient response times and maximize system lifetime.

Lifetime

Ships have a relatively long life span, reaching up to several decades. Although the market is accustomed to regular maintenance, major overhauls and life extension programmes, the power plant should ensure uninterrupted operation between maintenance intervals. In addition, maintenance costs should be acceptable. Ideally, the maintenance interval of the fuel cell system is aligned with the planned dry-docking of ships.

Fuel cell systems have few moving parts. Therefore, mechanical wear and tear is of less concern compared to rotating equipment. When properly designed, fuel cells have the tendency to degrade rather than fail. The rate of degradation, usually expressed in a % of power loss per 1000 hours, typically determines the number of running hours the system can be operated before the stacks need to be replaced. The mechanical balance of plant components usually have a longer life time.

Degradation of the fuel cell stacks is governed by cell design (materials and architecture) and operating conditions and load profile. For example, the life time of fuel cells can be extended with a higher catalyst loading, but this increases the capital cost of the system. Similarly, favourable operating conditions can decrease the rate of degradation, but may induce larger systems, higher fuel consumption or reduce transient capabilities. Dynamic load profiles also can cause strain on a fuel cell, what can be seen in automotive fuel cell systems which offer high power densities and excellent transient response but a lifetime limited to only 5000 hours. Heavy duty systems can reach over 30000 operational hours by compromising cost, specific power and transient capabilities. However, the effect of the saline marine environment on the lifetime of fuel cell systems has hardly been studied.

4.1.2 Business case

The business case for maritime fuel cell application is difficult today because:

- Fuel cell systems are relatively expensive;
- Alternative fuels, such as hydrogen, are relatively expensive as well.

Since both CAPEX and OPEX are still relatively high, there is basically no return on investment without subsidies and/or taxes on more polluting options. An exception would be the use of an SOFC fuelled by LNG, since the SOFC has a substantially higher electrical efficiency than conventional gas generators, thus providing savings on the OPEX side. Similarly, fuel cells may offer a return on investment in general due to their high electrical efficiency in case alternative fuels like hydrogen, ammonia and methanol are to be used. The price of fuel cells is expected to decrease as the production volume increases, due to large scale manufacturing and incremental learning. However, prices may also be reduced by more efficient use of rare (noble) materials used, recycling of materials, improved manufacturing methods and improved stack and module design. Hybridisation with auxiliary energy storage systems, such as batteries, supercapacitors and flywheels may allow to reduce the power installed on board. Finally, the modular nature of fuel cells may omit the need for an emergency back-up generator, while the low noise and vibrations offer flexibility in ship design and the removal of isolation and silencers, leading to further cost reductions.

4.1.3 Safety and classification

Ensuring safety of marine operations with fuel cells remains an important hurdle for widespread adoption, due to the absence of prescriptive rules regarding their implementation on ships. As a consequence, fuel cell-powered ships need to be approved via the alternative design clause. This route requests the owner to prove that the installation is at least as safe as a conventional power system through hazard identification and operability.

Marine fuel cell requirements differ from land-based applications with regard to testing criteria, reliability, availability and storage transport and processing of fuels. Points of attention in fuel cell design include segregation from external events, double barriers (air locks and double walled piping) for leak protection, leak detection and emergency shut-down procedures. Most classification societies, including Det Norske Veritas Germanischer Lloyd (DNV GL), Bureau Veritas (BV) and the American Bureau of Shipping (ABS), have developed guidelines for fuel cell application.

4.2 Inventory of (Dutch) knowledge

Maritime application of fuel cell systems is still in its infancy, but maritime application of fuel cells has been demonstrated in several projects, and many more are currently being carried out. Notable examples include:

- The FellowShip project demonstrated a 320 kW_e LNG-fuelled MCFC system on the offshore supply vessel Viking Lady
- The ZEMSHIP demonstrated a 96 kW_e PEMFC system on an inland passenger vessel Alsterwasser. 50 kg of hydrogen was stored on board at 350 bar
- METHAPU demonstrated a 20 kW_e SOFC fuelled with methanol on the car carrier Wallenius Wilhelmsen
- The Pa-X-ell project developed a 60 kW_e HT-PEMFC fuelled with methanol and demonstrated it on the cruise vessel MS Mariella
- In the SchIBZ project a 50 kW_e SOFC fuelled with low-sulphur diesel was developed and demonstrated on the multi-purpose vessel MS Forester
- The MARANDA project develops a 165-kW PEM fuel-cell powertrain able to provide power to a research vessel’s electrical equipment and its dynamic positioning while in research mode, in the extreme cold of the Arctic
- The FLAGSHIPS project will demonstrate that two commercial vessels, a push boat for river navigation and a car ferry can operate on hydrogen and fuel cells, with total 1 MW of PEM fuel cell power installed
- ShipFC will install 2 MW of SOFC fuel cell power running on green ammonia on the offshore platform supply vessel “Viking Energy”
- H2PORTS project will demonstrate at the Port of Valencia in real port operations, 2 dedicated equipment, specifically a reach stacker for container handling and a yard tractor for truck trailer handling, as well as a mobile HRS.

In fact, maritime fuel cell application is emerging on a variety of vessels in a large number of projects. These vessel type include:

- Ferries in the HySeas III, Water Go Round and ZEFF projects;
- A push boat in the ELEKTRA project;
- Inland vessels in the ISHY, FELMAR, WEVA, RiverCell and H2SHIPS projects;
- Inland container vessel MSC Maas (conversion by Future Proof Shipping and Nedstack);
- Cruise vessels as developed for Havila and in the NAUTILUS projects;
- A hydrogen water taxi in the H2Watt and SWIM projects;
- A crew transfer vessel Hydrocat;
- A Short-sea freighter in the SeaShuttle project;
- A construction support vessel designed by ULSTEIN (SX190);
- A sailing coach boat in the H2 Coach Boat consortium.

Research and development, testing, deployment and validation activities also often include the eco-system around the ship, namely port infrastructure:

- The RH2INE network of excellence aiming to deploy 10 hydrogen ships fuelled by at least three hydrogen filling stations on the Rhine between Rotterdam and Genoa by 2030;
- H_2 Filling Stations Den Helder, Damen Shipyards, Engie and the Port of Den Helder are developing a hydrogen refilling station (integrating locally a 2.6 MW solar park) for maritime and road transport use;
- Hydrogen Ships Lauwersoog is investigating the possibility of ships sailing on green hydrogen;
- THRUST consortium launches a commercial, emission-free solution for inland shipping, which can be scaled up towards the maritime sector (Rotterdam water taxi 2020);

On a scale broader than maritime, Dutch industry, research institutions, consulting firms, NGO's and government agencies are jointly working on a wide variety of projects aimed at validating and reinforcing the role of hydrogen in the energy transition to a sustainable and carbon-neutral energy system. Projects cover fundamental and applied topics related to:

- infrastructure (production, storage, transportation, distribution) treating both green and blue hydrogen as energy vector (the latter with CCS technologies);
- deployment (energy supply, industrial, mobility and transportation);
- legislative, regulatory and safety frameworks, standardization;
- entire eco-systems (hydrogen valleys and hubs, product life cycle).

They are often realized with partners from neighbouring countries. A rich overview of hydrogen activities in the Netherlands has been prepared by TKI Nieuw Gas and published in Spring 2020. For specific details, the reader is kindly referred to the corresponding document[45].

4.3 Scope for future research and development

4.3.1. New power system design based around fuel cells and its impact on ship design

Over the past decades, diesel engines and fuels have been stable factors in ship design, production, as well as CAPEX and OPEX estimations. Once the ships' power demand was determined, power train and fuel weights, volumes and system layouts followed established practices with the final details being set by the chosen brands. The transition to alternative energy conversion devices like fuel cells and different fuels (very often with different properties) leads to significant changes in weight and volume allocation on board, as well as the energy balance and management.

The gravimetric energy (MJ/kg) of hydrogen is about 3-times that of maritime liquid fossil fuels.. On the other hand, the volumetric energy content (MJ/L) of hydrogen is >6-times lower. Because of this, a ship powered by fuel cells will require a higher volume allotment than a comparable diesel-powered ship for the same transport mission (Figure 5). In addition, many of the alternative fuels cannot be stored in the conventional bunker arrangements below decks. Therefore, current diesel-based balance of volumes and weights is not usable anymore: a new power system design paradigm is needed.

With the very long life cycles of maritime assets and their high initial capital costs, addressing the existing fleet is important to achieve tangible results on the short- and mid-term. However, on the long-term, retrofitting and reconverting existing vessels is not an optimal solution, which comes with a blank sheet of paper and with developing a ship around a new fuel cell system solution.

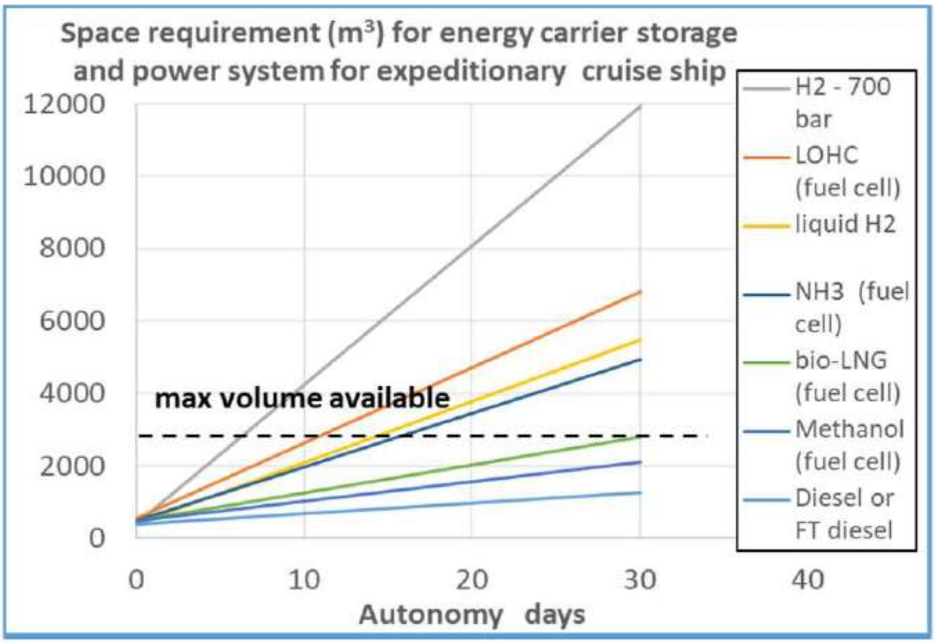

Figure 5. Specific energy density of various fuels set against energy density including packaging[46].

The general nature of such a project allows it to cover a very wide spectrum of activities, ranging from desk studies focusing on initial requirements, component life cycle, specific system engineering up to testing and validation of demonstrators. These activities can be formulated as the following three example phases.

- *1st phase example: system requirement definition and overall impact on ship design*

Determination of the missions, the required energy content and ranges, the operational areas and the ship-relevant technical, environmental and economic constraints for the selected ship types. Investigating relevant power system variants to achieve most efficient combinations of mass, volumes, energy efficiency, and environmental life cycle performance. Tasks include the following:

- Insight in mission needs and requirement definition: power usage, energy consumption (& fuel economy), heat and load fluctuations based on existing vessels with same/similar mission profiles;
- Evaluation of promising conceptual solutions for the power system: optimal options for a given mission: fuel cell, fuel type, fuel storage and fuel pre-treatment combinations;
- Understanding the life cycle of different system components: finding the balance between the cost and the lifetime (*important for modular system design, described in the 2nd phase example*);
- Initial power system impact on the overall ship design: evaluating the feasibility of promising solutions by considering boundary conditions & criteria (unacceptable ship size/cost and deviation from mission requirements).

- *2nd phase example: modular power system design*

From a systems perspective, modularity is a strategic approach to handle complexity by dividing a system into manageable, self-contained parts leading to simplified integration (along with future upgrades via periodic equipment overhauls), higher operational flexibility, adapting to eventual changes in the operating environment of the vessel: regulations, technology, missions, markets, fuel prices and availability, with the possibility of upscaling. Tasks could include the following:

- System architecture and function structure

The sub-division of the complete power system of the ship into well-defined modules following a core principles, functional breakdown structure, including: energy storage, energy conversion, power production, thermal management, power control, etc. All dependencies between components and sub-systems are identified, and based on this, the modular architecture is determined;

- Feasible power system solutions

Defining the strategy and rules for the recombination of these modules into feasible power system solutions, based on the promising findings in *phase 1* regarding the performance of various fuel cell-based power system configurations;

- Depth of modularity

Module grouping should be done in such a way that allows maintaining a high degree of functional independence (including the choice of modularity concepts for each part of system, e.g. sectional modularity, common bus, slot, stack, component sharing, component swapping, etc.). This task should aim to determine the optimal level of modularity and flexibility that takes into account component overall cost, lifetime, future changes like equipment overhauls, regulations and mission requirements, uncertainty in technology etc.;

- *3rd phase example: system construction, integration and testing*

Physical realization(s) of power system(s) by linking physical components to functions resulting from the previous analysis. Assessing the consistency of the power systems with the principles of modular architecture and drawing lessons for future follow-up steps.

- Laboratory testing and validation;
- The integration of a modular power system solution into the design of the vessel: first integration experiences.

System integration, access (time, cost), space considerations, hull integrity, weight, structural support and stability, operational aspects, such as retrofits, replacements and maintenance. This forms the basis for evaluating modularity metrics of interconnections and flexibility of the platform with weighted cost and volume information used to review KPIs, establish good practice based on lessons learned that would benefit any future development and integration endeavours.

The principle expected outcomes of such a project can be listed as the following:

- Identifying feasible solutions per ship type/ship size combinations;
- Modular, scalable and adaptable architecture approaches for ship power systems and energy carrier storage configurations;
- New ship design paradigms including new ship layout concepts;
- Understanding the impact of system design on lifetime performance & TCO;

- Fuel cell-based power system design guidelines including energy carrier storage.

4.3.2. Durability, efficiency and safety

Today's state of the art low temperature fuel cell technology enables high energy efficiency, high power density and fast response to load transients. Although the technology is already applied in cars, busses and trains, application in ships introduces new challenges. These are imposed by the distinctively different environment and duty cycle imposed on the system.

Fuel cell systems are typically composed of a number of smaller modules. For each individual fuel cell module, operating conditions that facilitate high system efficiencies do not necessarily result in high power density, low degradation and fast response to load transients. Therefore, fuel cell model design faces a trade-off between fuel consumption, power density, system lifetime and dynamic capabilities.

On a system integration level, a power and energy management system is needed to determine the number of modules required to deliver the required power with the optimal overall loading (to reach the highest possible efficiency), number of system start/stops & running hours (to optimize maintenance intervals) as well as to cause lowest degradation possible (to reach the longest lifetime).

Auxiliary energy storage devices, such as batteries, may provide additional flexibility to the fuel cell system. Hybridisation allows to operate fuel cells at their most efficient load, reducing fuel consumption. In addition, power peaks can be shaved by auxiliary energy storage devices which might improve system lifetime. However, hybridisation adds another degree of complexity to the power and energy management optimisation problem.

Moreover, when considering storing large amounts of energy for a heavy duty application like maritime, safety should be on the forefront of research and development actions. This holds true especially when energy carriers like hydrogen (and hydrogen-based compounds like methanol and ammonia, which is relatively new in shipping) is being considered as fuel. Hydrogen may have significant safety implications compared to conventional fuels such as diesel, for which the storage conditions are different, i.e. tanks are much larger and more likely to get damaged. The handling of the bunkering equipment can be different with extremely high pressure, low temperatures and the need for venting.

There are already commercial solutions for high pressure storage of hydrogen in cylinders, which are subjected to extreme scenarios via the thermomechanical testing for qualification. Nevertheless, use of high pressure (or cryogenic) tanks require case specific evaluation regarding safety zones, distances, fire and explosion protection and other risk mitigating measures. Investigation is needed with respect to the efficient and safe onboard storage and use under maritime conditions, taking into account aspects such as pressure, temperature, explosion risk and toxicity.

Learning from the introduction of LNG as an alternative fuel for trucking and inland and maritime shipping, tackling safety issues at an early stage will help significantly in the approval of the fuel by regulators, such as governmental agencies (e.g. Rijkswaterstaat, IL&T).

The following three example phases can constitute one such project.

- *1st phase example: fuel cell system optimisation and durability studies*

Looking into degradation phenomena that are most relevant (and mostly accentuated) in the maritime environment. As a response, an adequate power and energy management system can be proposed:

- Effect of module size and design on physical dimensions and fuel efficiency;
- Degradation phenomena in marine environment and for maritime duty cycles;
- Implications on CAPEX and OPEX;
- Optimisation for lowest TCO through:
    - Fuel cell system design and modularity
    - System hybridisation with energy storage (i.e. batteries)
    - Energy management system (EMS)

➢ *2nd phase example: desk/orientation study "why and when things can go wrong"*

Identifying risk factors for fuel cells and fuel cell system components in maritime conditions:

- Fuel cell system design;
- Fuel and air supply systems;
- Resilience to ship motions;
- On-board storage and tank bunkering procedures (risk matrix example on *Figure 6*);
- Ashore bunkering facilities using compressed gaseous and liquid hydrogen as well as other hydrogen storage materials (i.e. hydrides and organic carriers).

The PHA used the risk evaluation system shown in Figure A-2. This matrix integrates event severity and event frequency to produce four categories of risk. These categories are High Risk (HR), Medium Risk (MR), Low Risk (LR), and Routine Risk (RR).

Consequences	Category	Descriptive Word	Probability A Frequent	B Reasonably Probable	C Occasional	D Remote	E Extremely Remote	F Impossible
	I	Catastrophic						Hose rupture
	II	Critical					Nozzle leak	
	III	Marginal					Compressor failure	
	IV	Negligible						

High Risk	Moderate Risk	Low Risk	Routine Risk

Figure A-2. NREL risk matrix

Figure 6. Example of a general hydrogen refuelling process risk matrix[47].

- *3rd phase example: safety testing*

Various items can be tested as a validation of the previous risk assessment. These tests will point out the equivalent safety of the hydrogen application compared to reference fuels:

- Material safety: deterioration of material due to long time exposure in maritime conditions
- Component safety: testing of components under high pressure or extremely low temperature;
- Modular safety: functionality testing under operating conditions;
- Equipment safety: operational testing under normal and abusive conditions to assure all safety systems are fully functional;
- Environmental safety: impact of on and offshore storage in case of a calamity.

- *4th phase example: full system testing and demonstration*

Aforementioned desk studies and tests can eventually lead to a physical demonstration of the feasibility to store and use hydrogen as fuel on a medium and large scale in a realistic environment together with an adequate energy management system using a representative shipping power profile.

The expected outcomes of such a project can be listed as follows:

- Models of PEMFC modules for different stack sizes and nominal powers useful for determining fuel efficiency and effects of load transients;
- Increased knowledge on degradation for different loads, conditions and start/stop cycles;
- Increased knowledge on hydrogen fuel handling and behaviour in maritime conditions;
- Identifying and highlighting safety-critical aspects related to hydrogen as fuel;
- Concrete and experience-based information resulting from this project can be provided as input to regulation, code and standard definition for hydrogen as fuel in shipping.

4.3.3. Combined cycle solutions

The previous research themes deal with the design aspects as well as hurdles related to durability, efficiency and safety of fuel cells applied on ships. In addition, there are several ideas to further enhance fuel cell efficiency by combining fuel cells with thermal bottoming cycles. This is most commonly considered for the SOFC due to its elevated operating temperature. Examples are:

- SOFC-gas turbine combined cycles. Such a system has been developed by Mitsubishi Power and a pilot product named 'MEGAMIE' is being developed, which achieves efficiencies >55%.
- A Rankine cycle can be used to produce additional electric power from waste heat. Such systems have been developed for conventional internal combustion engines.
- High temperature waste heat from SOFCs can be used in a so-called triple effect cycle, where they are combined with an absorption refrigeration cycle to produce electricity, heat and cooling.

- The GasDrive project studied combined operation of an SOFC with an internal combustion engine, where hydrogen from the SOFC outlet was used to aid natural gas combustion in the engine.
- The internal fuel conversion capability of SOFCs enables their use as an electricity producing fuel pre-processor both for internal combustion engines and low temperature fuel cells.

- *AmmoniaDrive*

AmmoniaDrive is an initiative from the TU Delft led by dr. ir. Peter de Vos. The idea builds on the foundations of the GasDrive project, but aims to use ammonia as a fuel instead of LNG. Ammonia is considered a promising renewable marine fuel since it can be produced efficiently from renewable electricity and abundantly available materials and is more easily transported and stored than hydrogen. Despite its attractive prospects as an energy vector, ammonia has low flame speed and its use in engines typically requires a combustion improver. Hydrogen can be used to stabilise ammonia combustion, and can be generated by decomposing some of the ammonia prior to the engine.

AmmoniaDrive takes advantage of the internal ammonia decomposition possibilities on the fuel electrode of SOFCs. High temperature waste heat from the SOFC is used to decompose ammonia internally, and the hydrogen left in the exhaust gases is blended with ammonia and subsequently used in an internal combustion engine. Ammonia is also used to remove potential NO_X emissions from the engine exhaust gas using selective catalytic reduction (SCR).

The AmmoniaDrive system is envisioned to achieve:

- High efficiencies through the use of a direct ammonia SOFC
- Good transient capabilities provided by the ICE
- No hazardous emissions due to the use of an SOFC and SCR
- Low total cost of ownership

In terms of TRL, the highlighted projects can be defined as follows:

Development Research Actions (TRL 3-5)

- Optimising FC modules for maritime use cases, including work on the balance of plant and fuel storage: different combinations of fuel cells, novel balance of plant configurations and different hydrogen carriers and possible reforming options to increase operational flexibility and FC durability;
- Infrastructure: how to store and bunker very large volumes of energy in ports (compressed gaseous and liquid hydrogen, hydrogen carriers).

Demonstration Actions (TRL 5-7)

- Define regulations for bunkering, standards and rules on hydrogen and FCs in maritime (ship specifications, acceptance of on board storage of pure hydrogen or H_2 carriers).

TRL actions sourced from the Hydrogen Europe and Hydrogen Europe Research Strategic Research and Innovation Agenda, July 2020[48].

5. Conclusions and recommendations

Increasing societal demands to reduce emissions from shipping drive the adoption of renewable fuels and low emission drive systems. Fuel cells can electrochemically convert a variety of fuels directly into clean electricity silently with high efficiencies and without hazardous emissions. The maritime applicability of fuel cell technology is assessed in this report, discussing state of the art fuel cell technology, alternative fuel options and fuel preparation. This inventory is subsequently used to analyse potential business and use cases, identify challenges and opportunities and define the scope for future research and development activities.

Three fuel cell types are identified as promising for ships: both the low and high temperature polymer electrolyte membrane fuel cells (LT/HT PEMFC) and the solid oxide fuel cell (SOFC). LT-PEMFCs have matured rapidly in recent years by actors in the automotive sector. Maritime products are now emerging in the 100 kW power class with competitive specific powers and sizes, high efficiencies, fast load response stack and lifetimes over 30000 hours. To achieve these figures, LT-PEMFCs require a high-purity hydrogen for which a storage and bunkering infrastructure is still largely inexistent.

HT-PEMFCs have a higher tolerance to fuel impurities, most notable carbon monoxide. Therefore, these are typically combined with internal fuel reformers. Products are available with an integrated methanol reformer, but in the kW power class. The technology is somewhat less mature than its low temperature counterpart, and so is it’s specific power, efficiency, load response and lifetime as of today. SOFCs are arguably more mature, with products in the hundred kilowatt scale already on the market. Their operating temperature, ranging from 500°C to 1000°C, enables (partial) fuel processing directly on the fuel electrode and high electrical efficiencies. However, specific power and load response are still inadequate for wide adoption in shipping.

All fuel cell types face a number of common challenges, albeit to a variable extend. The production volume of fuel cells is low compared to conventional marine power and propulsion systems, limiting the power output of individual modules as well as their availability. Although the increased modularity is an advantage regarding system redundancy, it increases specific cost, requires more cables and piping, and results in more installation and maintenance costs. A direct consequence is a relatively high capital cost compared to internal combustion engines. This becomes even more challenging if the stack replacement interval is short compared to internal combustion engine overhaul. Although the cost of LT-PEMFCs is decreasing in recent years, high temperature fuel cells are still relatively expensive. Another important hurdle is the absence of design guidelines and prescriptive rules for fuel cell application on ships.

The application of fuel cells on ships is and has been studied and demonstrated in a large number of projects, for various fuel cell types and including many different ship types such as ferries, canal boats, inland vessels, offshore supply vessels and cruise ships. It is expected that fuel cells will become a feasible alternative for vessels with a relatively low installed power and operating range at first, especially those operating in coastal waters with high regulatory pressure to reduce emissions, which could subsequently allow incremental learning and scale-up towards higher powers and endurances.

Three research and development themes are identified, which should address some of the important hurdles for wide adoption of fuel cell systems on ships. The first theme deals with the identification of feasible solutions for different ship types, development of modular, scalable and adaptable architectures and new design paradigms for ships with drive systems incorporating fuel cells. The second theme addresses the durability, efficiency and safety of marine fuel cell systems themselves.

The last theme deals with the development of systems were fuel cells are combined and even integrated with bottoming cycles or internal combustion engines.

In terms of the wider implications of R&D themes, the development and definition of novel system architectures as well as creating better awareness of risks and safety requirements can lead to earlier system adoption and design optimization, ultimately resulting in long-term savings. The gained insights allow for an earlier and more advantageous positioning on relevant markets. Active participation of key maritime stakeholders in such knowledge- and experience-based R&D can highlight unique opportunities. However, the outcomes resulting from such projects can create impact reaching far beyond the consortia members themselves: a concerted effort and focus can generate enough stakeholder momentum to steer and accelerate the process of creating necessary regulatory frameworks, facilitating widespread introduction of fuel cells in the sector. Moreover, as the technology matures and its viability is demonstrated, the confidence of relevant actors and the general public increases, which is of crucial importance for its progressive acceptance and wider usage. Finally, highlighting the shortcomings and improvement potential of hydrogen and fuel cell technology can lead to the concretization of development roadmaps specific to maritime applications.

Over the years, the maritime industry has proved its resilience and high degree of flexibility. It is reasonably safe to assume that the transition from fossil fuels to their sustainable alternatives will be no different. As is the case today, the future of shipping will most likely remain rich in choice when it comes to fuel selection and propulsion system configuration – tailored specifically to mission specification and the need of the operator: different technological solutions will suit different applications best. While smaller and medium-sized vessels can easily run on hydrogen, larger ocean-going vessels may run on ammonia and other energy-dense fuels. Fuel cells offer several advantages over conventional internal combustion engines, are maturing rapidly and can be used in ships already today. However, several barriers still hinder wide adoption. Research and development focus is placed heavily on driving the cost down to increase competitiveness, increase system reliability and availability, study and improve safety and general user experience. The numerous demonstration vessels that entered active use and that have been deployed for sea trials serve that exact purpose.

A new shipping ecosystem is in the making. A holistic approach, including a broad expertise in system design, is needed to combine innovations on the vessel and inside ports into viable solutions that will clear the path towards a more sustainable maritime industry. Fuel cell technology fits in such an approach.

Abbreviations

AFC	Alkaline Fuel Cell
BoP	Balance of Plant
BtL	Biomass-to-Liquid
C_2H_5OH	Ethanol
CCS	Carbon Capture System
CH_3OH	Methanol
CO	Carbon monoxide
CO_2	Carbon dioxide
DMA	Distillate Marine Fuel
DME	Dimethyl ether (CH_3OCH_3, simplified to C_2H_6O)
DMFC	Direct Methanol Fuel Cell
EMSA	European Maritime Safety Agency
FAME	Fatty acid methyl esther
FC	Fuel Cell
GHG	Greenhouse gas
H_2	Molecular hydrogen
H_2O	Water
HESC	Hydrogen Energy Supply Chain
HFO	Heavy Fuel Oil
HT-PEMFC	High Temperature Polymer Electrolyte Membrane Fuel Cell
HVO	Hydrotreated Vegetable Oil
IMO	International Maritime Organization
LNG	Liquified Natural Gas
LSMGO	Low Sulphur Marine Gas Oil
LT-PEMFC	Low Temperature Polymer Electrolyte Membrane Fuel Cell
MCFC	Molten Carbonate Fuel Cell
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
N_2	Molecular nitrogen
NH_3	Ammonia
O_2	Molecular oxygen
OECD	Organisation for Economic Co-operation and Development
PAFC	Phosphoric Acid Fuel Cell
PrOx	Preferential Oxidation
PSA	Pressure Swing Adsorption
R&D	Research and Development
SMET	Selective Methanation
SOFC	Solid Oxide Fuel Cell
SSAS	Solid State Ammonia Synthesis
ULSHFO	Ultra-Low Sulphur Heavy Fuel Oil
WGS	Water Gas Shift

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Appendix 1: Webinar FCMAR

Webinar FC MAR – Minutes of MS Teams meeting

Date: 17 September 2020

Time: 10.00 – 11.30 hr

Participants: Peter Borkens (Atomic One), Isaac Barendregt (DMO), Jan van Beckhoven (HyMove), Benny Mestemaker (IHC), Christiaan Veldhuis (Marin), Pieter 't Hart (MKC), Arwout Verwoerd (MTU), Arjen Uytendaal (NML), Nathalie Nipius (NML), Jan Egbertsen (PoA), Loek Verheijen (Rijksrederij), Carina Jansen (Rotortug), Maurice Luijten (RVO), Kamil Mrozewski (TNO), Lindert van Biert (TUD) , Robert Hekkenberg (TUD), Klaas Visser (TUD), Jesper Zwaginga (TUD), Wiard Leenders (Voyex),

1. Introduction

Pieter 't Hart opens the meeting and welcomes the participants to this webinar. After a short introduction of the FCMAR project, Kamil Mrozewski of TNO gives an overview of the current state of the art and the first research theme 1. New power system design based around fuel cells and its impact on ship design.

Lindert van Biert of TU Delft gives an overview of theme 2 Durability, efficiency & safety of fuel cell technology and theme 3 Ammonia Drive.

After the presentation, time for questions and answers is planned.

Wiard Leenders of Voyex asks why the focus is on fuel cells and not on internal combustion engines. Pieter 't Hart explains that MKC , TNO en TU Delft have carried out several projects on alternative fuels in internal combustion engines in the last years. This is a new project that has a special focus on fuel cells for the maritime sector.

Wiard Leenders asks what is meant by the word high power density and why HT PEM fuel cells have a potential for a lower cost price. Lindert agrees that not all fuel cells are equally power dense and that weight and volume must be taken into account in the ship design process. Kamil mentions that HT-PEM has a potential for a lower cost price since less catalyst is required due to higher operating temperature (although membrane durability is an issue with regard to leakage).

Finally Wiard Leenders asks what the opinion is on the slide of Ballard stating a 30k hour lifetime for operation. Kamil says that 30k hours lifetime for heavy-duty applications is state of the art and coincides with 5, 7 or 9 year ship overhaul periods. The number strongly depends on the way the fuel cell is operated, because with many dynamic load changes this time will certainly be reduced.

Christian Veldhuis of Marin asks what the dynamics are for the different fuels cell with different loads. LT-PEM stabilizes within seconds, HT-PEM within minutes and SOFC within about 15 minutes. Christian states that Marin works with PEM but not with SOFC (yet) and wonders whether this SOFC performance is expected to improve in the coming years. Lindert comments that modern SOFCs do start up considerably faster than older SOFCs, however, it still takes about 15 minutes to an hour to reach a stable operating point. This is expected to improve in the coming years.

Klaas Visser of TU Delft stresses the importance of hybrid configurations like Ammonia Drive with ICE and SOFC and/or batteries, supercapacitors but also a combination of LT-PEM, HT-PEM and SOFC. Klaas Visser proposes to include the storage of H_2 in solid materials (metal hydrides or chemical hydrides). Lindert responds that these storage solutions are included in the presentation as organic H_2 carriers.

Loek Verheijen of Rijksrederij states that the fleet of Rijksrederij also contains several inland vessels and wonders if the rapid developments in automotive (light- and/or heavy-duty) can be used for ships. Kamil agrees on that point but also mentions cars have very different dynamic loads compared to ships. Trucks and ships are better comparable with regard to load profiles but, at least at this moment, there is no easily transferrable plug and play solution. The effects of scale play an important role and the sizing of the fuel cell and energy storage (batteries) is a key topic. Wiard Leenders agreed that when he worked at Damen they studied the use of automotive fuel cells for marine application, but that was not a good fit.

For small vessels a small fuel cell unit and a large battery can offer a solution.

Peter Borkens of Atomic one works on injection of Hydrogen in internal combustion engines via cracking and works with UT, HAL and Sandfirden on a project with TRL level 7/8 and is interested in co-operation.

Isaac Barendregt of DMO concludes from the presentation that HT-PEM could be the ideal fuel cell for maritime application and questions if research on HT-PEM is still ongoing.

Kamil says that HT-PEM is at low TRL level at the moment with durability being of the main bottlenecks (although improving). Next to this is the system power density, which is also quite low. Lindert says that Serenergy still invests in HT-PEM but efficiency level are currently between 30 and 40%. This might improve in the future.

Wiard Leenders of Voyex offers to assist when practical and safety questions arise and asks if the presentation and participants list can be shared. This will be the case.

Pieter ‘t Hart closes the meeting and thanks everyone for their participation. If there is any interest to participate in a project/theme please feel free to contact MKC, TNO and/or TUD. In December 2020 the consortium will finish the project with a final report that will be available for interested parties.

Appendix 2: Presentation FCMAR

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State of the art

- Low temperature PEMFC
  - High power density, good load transients, efficiency up to 60%
  - Bound to high-purity hydrogen, stored compressed, liquid or solid
  - Products with AiP available for powers ranging from 50 to 200 kW
  - Several demonstration projects, installed power 50 kW to ±1MW

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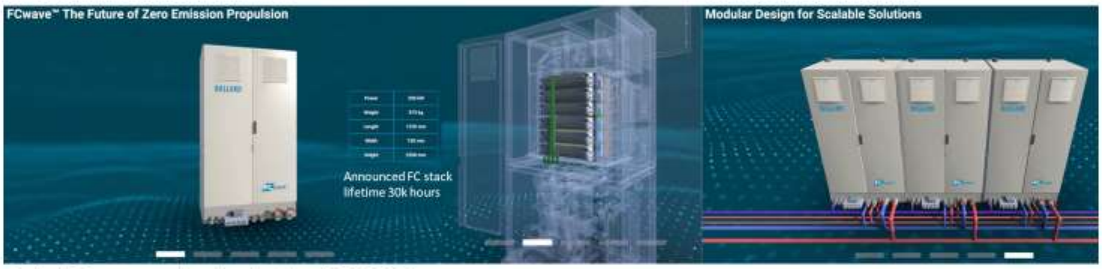
State of the art

- Low temperature PEMFC
  - Growing industry, latest product to be developed specifically for maritime:



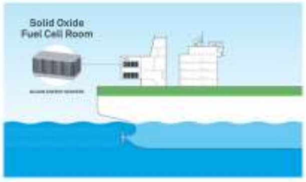
Ballard FCwave, product launched on 10-09-2020

State of the art

- High temperature PEMFC
  - Not bound to hydrogen with a high purity, waste heat recovery
  - Fuel treatment can be integrated in the system
  - Products on the market with power ranging from 5 to 30 kW
  - Demonstrators with methanol (Pa-X-ell)

State of the art

- High temperature SOFC
  - Fuel flexible, internal reforming possible, waste heat recovery
  - Products up to 300 kW for natural gas, efficiency up to 65%
  - Demonstration within METHAPU (methanol) and SchIBZ (diesel)
  - NAUTILUS project (LNG), Samsung & Bloom Energy (LNG), ShipFC (ammonia)



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State of the art

	LT-PEMFC	HT-PEMFC	SOFC
Operating temperature (°C)	65 - 85	140 - 180	500 - 1000
Electrical efficiency (% LHV)	40 - 60	40 - 50	50 - 65
Fuel requirements	99.99% H_2	CO < 3%	S < 20 ppm
Gravimetric power density (W/kg)	125 - 750	25 - 150	8 - 80
Stack life time (kh)	5 - 30	10 - 30	20 - 90
System life time	≥ 10 years with stack replacement		
Cold start-up time	<10 seconds	10 - 60 minutes	>30 minutes
Load transients (0 to 100%)	seconds	<5 minutes	<15 minutes
Current capital cost ($/kW)	1000 - 2500	3000 - 5000	3500 - 15000
Future capital cost ($/kW)	50 - 500	100 - 1000	200 - 2000
Maritime TRL (2020)	6 - 7	5 - 6	4 - 5

Summary

LT-PEM
- High gravimetric power density
- Good transient performance
- Durability for marine load cycles
- Fuel availability, storage & bunkering (H_2)

HT-PEM
- Impurity tolerance, heat recovery
- Durability, system dynamics

SOFC
- Fuel flexibility, heat recovery
- System dynamics, power density

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State of the art

	LT-PEMFC	HT-PEMFC	SOFC
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Maritime TRL (2020)	6 - 7	5 - 6	4 - 5

Challenges
- Production volume, availability
- Durability in marine environment
- Safety and classification, cost, cost & cost

Opportunities
- Compliance to regulations
- High system efficiency
- Flexible system design (modularity, scalability, adaptability, redundancy)

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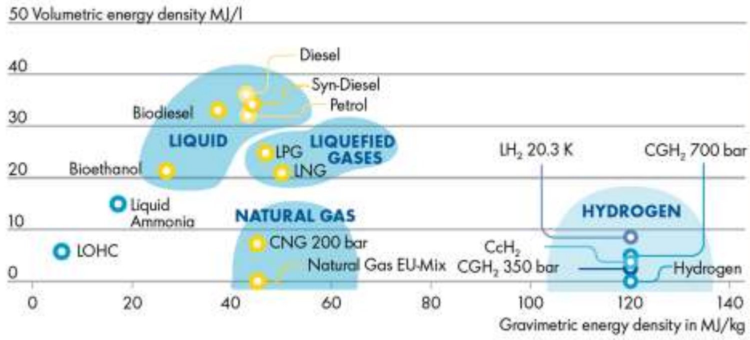
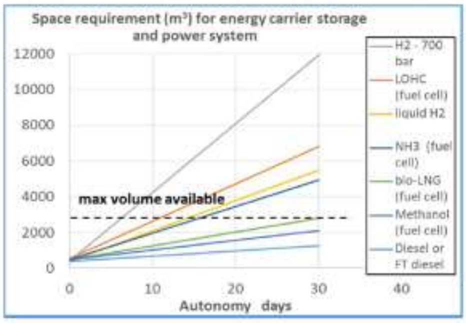
Theme #1
New power system design based around fuel cells and its impact on ship design

CONTEXT





W. Warnecke et al.: On route to CO_2-free future fuels: Hydrogen. Latest developments in its supply chain and applications in transport. 41st Vienna Motor Symposium, April 2020.

NAVITAS consortium, EU project proposal, 2019.

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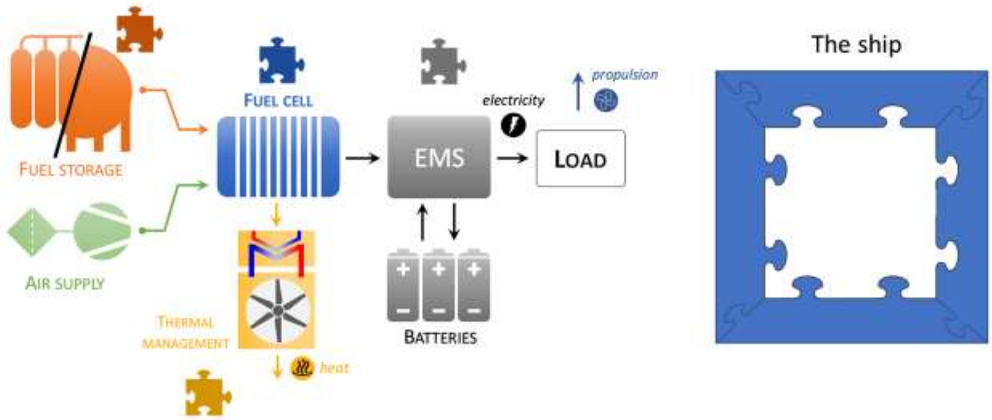
Theme #1

New power system design based around fuel cells and its impact on ship design

CONTEXT



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Theme #1

New power system design based around fuel cells and its impact on ship design

SCOPE

- *Example phase 1: system requirement definition and overall impact on ship design*

Defining requirements

Insight in mission needs and requirements
(based on existing vessels with the same/similar mission profiles)

- Power usage
- Energy consumption (& fuel economy)
- Heat and load fluctuations, etc.

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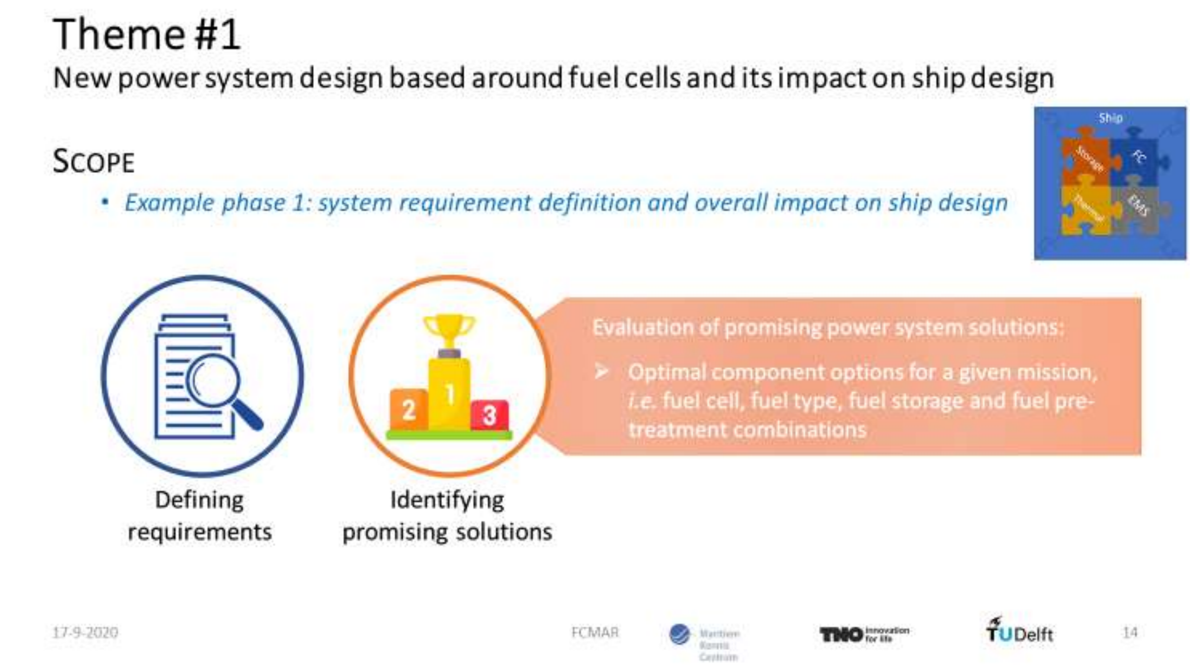
Theme #1
New power system design based around fuel cells and its impact on ship design
SCOPE
• Example phase 1: system requirement definition and overall impact on ship design
Ship
Storage
FC
Thermal
EMS
Evaluation of promising power system solutions:
➢ Optimal component options for a given mission, i.e. fuel cell, fuel type, fuel storage and fuel pre-treatment combinations
Defining requirements
Identifying promising solutions
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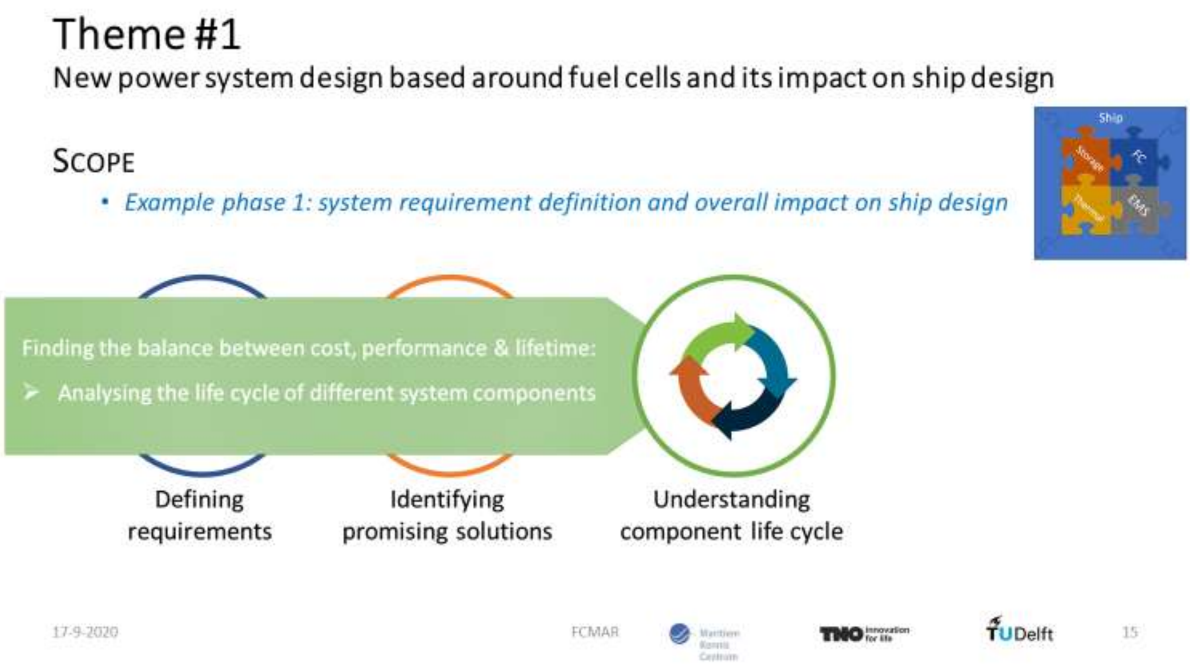
Theme #1
New power system design based around fuel cells and its impact on ship design
SCOPE
• Example phase 1: system requirement definition and overall impact on ship design
Ship
Storage
FC
Thermal
EMS
Finding the balance between cost, performance & lifetime:
➢ Analysing the life cycle of different system components
Defining requirements
Identifying promising solutions
Understanding component life cycle
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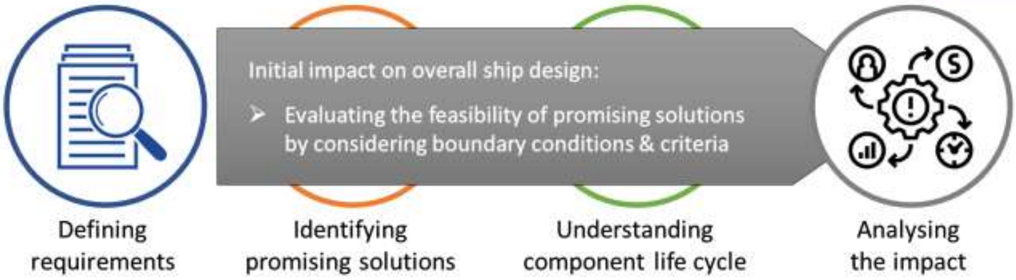
Theme #1

New power system design based around fuel cells and its impact on ship design

SCOPE

- *Example phase 1: system requirement definition and overall impact on ship design*



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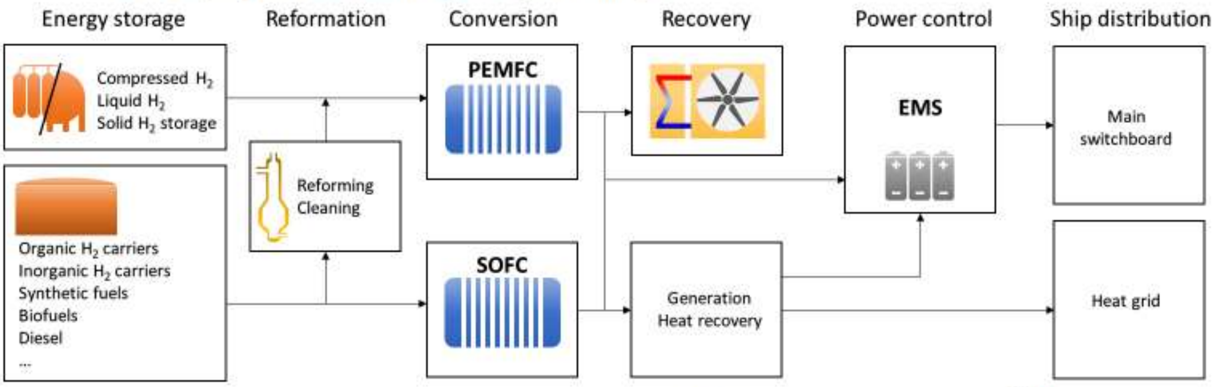
Theme #1

New power system design based around fuel cells and its impact on ship design

SCOPE

- *Example phase 2: modular power system design*



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Theme #1

New power system design based around fuel cells and its impact on ship design

SCOPE

- *Example phase 3: system construction, lab validation and/or integration and testing*

Physical realisation of power system(s):

- Laboratory tests and validation
- Integration of a modular power system solution into vessel design
- Test protocols and standardization
- Fuel storage and handling experience
- Drawing lessons learned

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Theme #1

New power system design based around fuel cells and its impact on ship design

PROJECT OUTPUTS

- Identifying feasible solutions per ship type/ship size combinations
- Modular, scalable and adaptable architecture approaches for ship power systems and energy carrier storage configurations
- New ship design paradigms including new ship layout concepts
- Understanding the impact of system design on lifetime performance & TCO
- Fuel cell-based power system design guidelines including energy carrier storage

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Theme #2

Durability, efficiency & safety

CONTEXT

- System performance in marine environment and for ship duty cycle
- Fuel cell system design for:
  - High power density
  - High efficiency
  - Durability
  - Transient capabilities
- Safety considerations for maritime application of fuel cell technology and hydrogen (based) fuels

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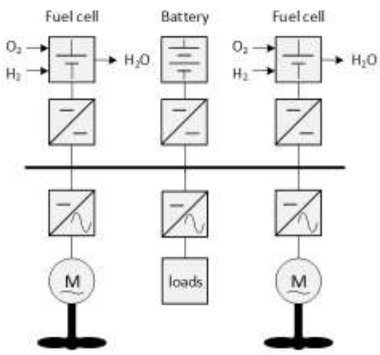
Theme #2

Durability, efficiency & safety

SCOPE

- *Example phase 1: fuel cell system optimisation and durability studies*



- Effect of module size & design on physical dimensions and fuel efficiency
- Degradation phenomena in marine environment and for maritime duty cycles
- Implications on CAPEX and OPEX
- Optimisation for lowest TCO through:
  - Fuel cell system design and modularity
  - System hybridisation with energy storage
  - Energy management system (EMS)

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Theme #2
Durability, efficiency & safety

SCOPE

- *Example phase 2: desk/orientation study "why and when things can go wrong"*

The PHA used the risk evaluation system shown in Figure A-2. This matrix integrates event severity and event frequency to produce four categories of risk. These categories are High Risk (HR), Medium Risk (MR), Low Risk (LR), and Routine Risk (RR).

Consequences		Probability					
Category	Descriptive Word	A Frequent	B Reasonably Probable	C Occasional	D Remote	E Extremely Remote	F Impossible
I	Catastrophic						Hose rupture
II	Critical					Nozzle leak	
III	Marginal					Compressor failure	
IV	Negligible						

High Risk	Moderate Risk	Low Risk	Routine Risk

Figure A-2. NREL risk matrix

C. Rivkin, R. Burgess, W. Buttner: *Hydrogen Technologies Safety Guide*. NREL publication, January 2015.

- Identify risk factors for fuel cells system components in maritime conditions:
  - Fuel cell system design
  - Fuel and air supply systems
  - On-board storage bunkering
  - Bunkering facilities

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Theme #2
Durability, efficiency & safety

SCOPE

- *Example phase 3: validation and testing of safety concept*

Tests to validate the previous risk assessment and point out the equivalent safety of the hydrogen and fuel cells compared to reference fuels and drive systems

- Material, component, modular, equipment and environment safety

- *Example phase 4: full system testing and demonstration*

Physical system demonstration

- adequate energy management system for a representative shipping power profile
- feasibility to store and use hydrogen as fuels on a medium and large scale

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Theme #2

Durability, efficiency & safety

PROJECT OUTPUTS

- Fuel cell models to simulate fuel efficiency and transient capability
- Knowledge on fuel cell degradation in marine environment and duty cycles
- Identification of safety-critical aspects related to hydrogen as a ship fuel
- Knowledge on hydrogen fuel handling and behaviour in maritime conditions
- Experience that can be provided as input to regulation, code and standard definition

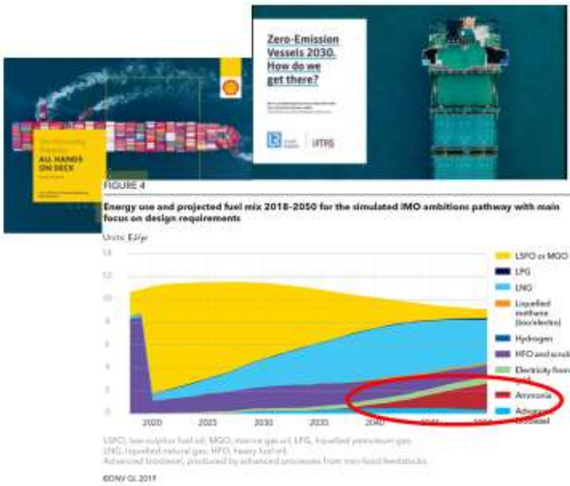
Contact: Peter de Vos, P.deVos@tudelft.nl

Theme #3

AmmoniaDrive

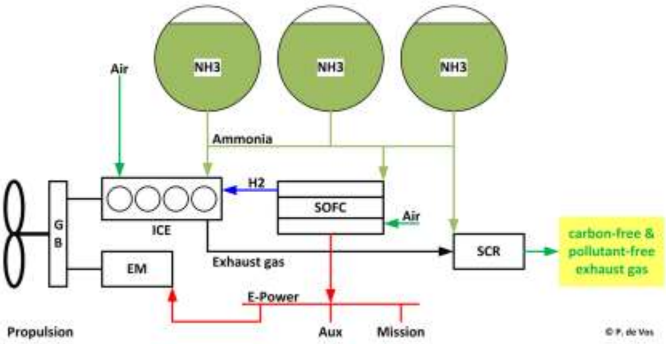
CONTEXT

- Ammonia is a low-cost alternative fuel with reasonable energy density
- Feedstock (air + water) is available everywhere
- No harmful emissions (also not in fuel synthetisation phase)
- Existing infrastructure and safety measures
- High efficiency



Theme #3
AmmoniaDrive

CONCEPT



- Fuel and power generation system need to match!
- Diesel fuels and Diesel Engines are a perfect match
- But for ammonia?

- ICE + ammonia ❌
- SOFC + ammonia ✅
- SOFC + Ship ❌

- AmmoniaDrive + ammonia ✅
- AmmoniaDrive + ammonia + Ship ✅

Theme #3
AmmoniaDrive

SCOPE

- Low TRL → fundamental & applied technological research required
- Effects of ammonia spills unknown → fundamental & applied biological research

NWO PERSPECTIEF PROPOSAL

- PhD 1: NH3-fuelled SOFC (TUD/RUG)
- PhD 2: NH3-AOG combustion (RUG/TUD)
- PhD 3: NH3+AOG-fuelled ICE (TUD/RUG)
- PhD 4: NH3 spill environmental impact (WUR)
- PhD 5: NH3 safety & maintenance (TUT)
- PhD 6: AmmoniaDrive system integration, performance and control (TUD/TNO)
- PD: scaled system demonstrator (TNO/TUD)

Theme #3
AmmoniaDrive

Current consortium
- TU Delft, TNO, MKC, DOTC, C-Job
- MARIN
- RUG, WUR & TUT (pending)

Looking for
- AmmoniaDrive enthusiasts & consortium partners
- Support letters and in-kind / cash contributions for NWO Perspectief proposal

Further info? Please read SWZ article: https://research.tudelft.nl/en/publications/ammoniadrive-a-solution-for-zero-emission-shipping

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Contact: Peter de Vos, P.deVos@tudelft.nl

Theme #3
AmmoniaDrive

Activities & dates
- MKC MT: AmmoniaDrive Pitch 3 September
- GasDrive user committee meeting: AmmoniaDrive Pitch 10 September
- MIIP meeting: 14 September
- AmmoniaDrive information and consortium formation meeting: 13 Oktober
- Fase 1 Perspectief: 22 Oktober 2020
- Fase 2 Perspectief: 15 December 2020
- Fase 3 Perspectief: 15 Juni 2021

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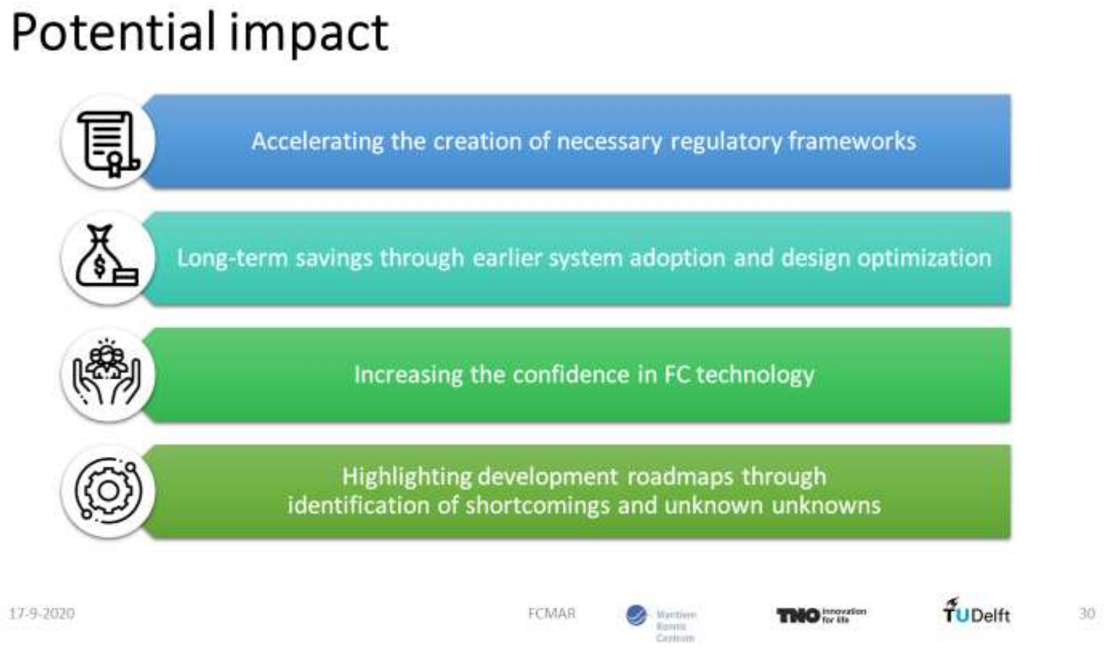
Potential impact
Accelerating the creation of necessary regulatory frameworks
Long-term savings through earlier system adoption and design optimization
Increasing the confidence in FC technology
Highlighting development roadmaps through identification of shortcomings and unknown unknowns
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