Comparative analysis of alternative fuels for marine SOFC systems

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COMPARATIVE ANALYSIS OF ALTERNATIVE FUELS FOR MARINE SOFC SYSTEMS

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Abstract. To continue its operations, the marine industry needs to comply with emission regulations. Solid Oxide Fuel Cells (SOFCs) are considered a promising solution, since it can generate energy athigh efficiency and low NOX, SOX and particulate matter emissions. Another advantage of SOFCsis fuel flexibility, meaning several fuels can be applied in SOFC systems. This brings up the questionwhich fuel is most effective for a marine SOFC system. In this research, marine gas oil (benchmark),liquefied hydrogen, biodiesel, Fischer-Tropsch diesel, natural gas, methanol, dimethyl ether, and hydrogenare compared as bunker fuel. A comparison framework is proposed specialised for marineapplications. The following decision criteria are selected: production capacity, volumetric/ gravimetricenergy density, technological readiness, safety, fuel cost, cost of the fuel storage system, and emissions. The performance indicators are quantified for every fuel based on literature and supplier information.In the end, five alternative fuels are selected for marine SOFC systems on the selected criteria, whichwill be used in further research.

Keywords: Marine fuels, Power generation, SOFC, Emissions.

1. Introduction

1.1. Marine emissions and regulations

The sixth climate change assessment report by the Intergovernmental Panel on Climate Change (IPCC) [1] urges that reductions in greenhouse gas emissions should be accelerated to succeed in limiting global warming to 1.5 °C above pre-industrial levels. According to the fourth greenhouse gas study by the International Maritime Organisation (IMO), the shipping industry generated 2.9% of global anthropogenic emissions. Moreover, fossil fuel combustion in marine engines causes pollutant emissions. In 2017 in Europe, the marine industry contributed 19% to NO emissions, 11% to SO_X emissions and 8% to particulate matter (PM) emissions [2]. In 2018, IMO set a goal of 50% greenhouse gas (GHG) emission reduction in 2050 compared to the levels in 2008. CO_2 emissions are regulated with the Energy Efficiency Design Index (EEDI) and the established Emission Control Areas (ECAs) have limits on NO_X, SO_X, and PM emissions.

1.2. Use of alternative fuels

There are many areas of development in the decarbonisation of the marine industry. IMO point out a large potential in the use of alternative fuels, see Figure 1.. Xing et al. [3] concluded in a comprehensive review of CO_2 reducing technologies that the use of alternative fuels and application of alternative energy converters can have the most significant impact. Alternative marine fuels include diesel, vegetable oil, natural gas, methanol, ethanol, dimethyl ether (DME), hydrogen, and ammonia. Most fuels can be produced from different feedstock, which has a significant impact on the cost and emissions of the fuel over its life cycle. The technical performance and other characteristics, such as availability, cost, infrastructure and environmental impact vary for these fuels, influencing their potential for marine propulsion [4]. The shipping industry is occupied with the selection of alternative marine fuels by evaluating a wide range of criteria.

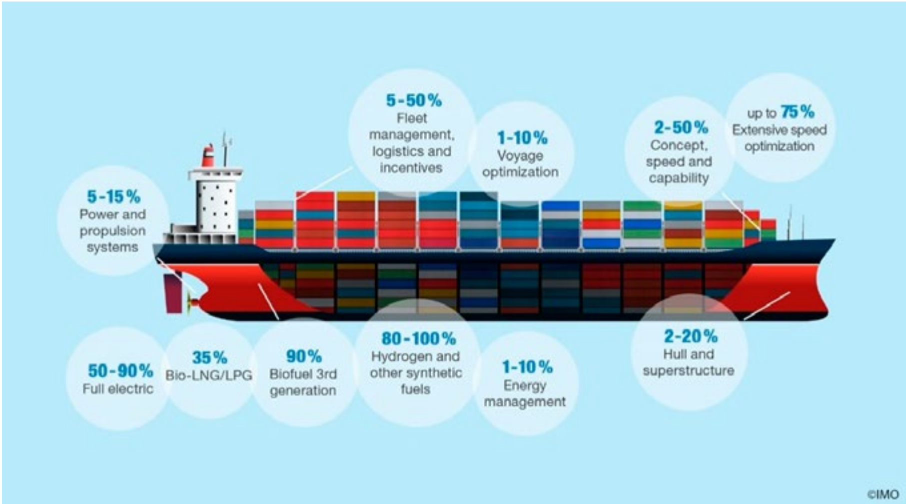


Figure 1.: Areas and potential of decarbonisation of marine industry on technical and operational level.

1.3. SOFCs and fuel-flexibility

Fuel cells convert chemical energy directly to electrical energy and many of the considered alternative fuels can be used. There are many types of fuel cells, but Low-Temperature Proton Exchange Membrane Fuel Cells (LT-PEMFC) and Solid Oxide Fuel Cells SOFC are most often considered for marine applications Baldi2020. Although hydrogen-fuelled LT-PEMFCs can produce power at high efficiency with virtually no local emissions, van Biert et al. Biert2016 concluded that this is not feasible for voyage times above 100 hours, because of the low energy density of stored hydrogen. Alternative fuels with higher energy densities can not directly be used in LT-PEMFC and require many fuel processing steps, which decrease the efficiency and power density of the s ystem. SOFC systems produce electric power at high efficiency (50-60%), while barely emitting NO_X and PM emissions, because there is no combustion in the cells [5]. Moreover, fuel cell systems are characterized by good part-load characteristics, high redundancy, little maintenance, and low noise and vibrations [6]. However, the application of SOFC systems in ships is still challenged with low power density, high investment cost, limited lifetime and slow response to dynamic loads [6]. Nevertheless, SOFCs offer high fuel flexibility [7] because methane, ethanol, methanol, DME and ammonia can be directly (or after minor fuel processing steps) fed to the SOFC, and fuel flexibility is considered a key aspect of the transition to renewable fuels [8]. Although several fuels have been evaluated theoretically and experimentally for SOFCs, it is not known which fuel performs best for a marine power plant.

1.4. Objective and Outline

This paper proposes a decision framework for the evaluation of alternative fuels for marine applications, which is presented in section 3. In this research, the framework is used for evaluation of the fuel possibilities for a marine SOFC power plant. Section 2. describes the considered fuels, and the performance parameters are quantified and compared based on literature and supplier information in section 4. The outcome of the evaluation and suggestions for future work can be found in section 5.

2. Alternative fuels

The considered alternative marine fuels are provided in Table 1. and include hydrogen, biodiesel, Fischer-Tropsch diesel, methanol, DME and ammonia. Marine gas oil (MGO) fuelled is also included as benchmark. The fuels and their applicability to SOFC are described in the following sections. Table 2.

Table 1.: Alternative fuels that are of interest to marine industry and can be used with SOFC, including their onboard storage technique selected in this study.

Short	**Fuel**	**Storage technique**
MGO (benchmark)	Marine gas oil	Liquid (Amb. T)
LH2	Hydrogen	Cryogenic (-253°C)
BIO D	Biodiesel	Liquid (Amb. T)
FT D	Fischer-Tropsch Diesel	Liquid (Amb. T)
LNG	Liquified Natural Gas	Cryogenic (-162°C)
MeOH	Methanol	Liquid (Amb. T)
DME	Dimethyl ether	Compressed (5 bar)
NH3	Ammonia	Cryogenic (-33°C)

summarises the advantages and disadvantages of the different fuels for SOFC systems in marine applications.

2.1. Diesel-type fuels

Currently, diesel-type fuels are dominantly used in ships. It is relatively cheap and energy-dense compared to alternative fuels. Moreover, its production and distribution infrastructure, as well as regulations, are in place. Due to these advantages, diesel has been often considered to fuel SOFCs in marine applications [9, 10, 11, 12]. However, diesel is inconvenient for SOFC, since it requires a complex and large fuel processing plant, which lowers the power density and efficiency of the SOFC system [13, 6].

Recently, low sulphur fuel oils and biodiesel have gained more attention in the marine industry, in order to meet emission requirements. Low sulphur fuel oil (LSFO), very low sulphur fuel oil (VLSFO), and ultra-low sulphur fuel oil (ULSFO), are limited to 1.0%, 0.5% and 0.1% sulphur content [14]. These fuels are beneficial for SOFC systems, because less desulphurisation is required. SOFCs may even be able to operate stably on ULSFO without desulphurization, albeit with a small performance drop caused by sulfur poisoning [15]. However, the aforementioned fuels are more expensive, since additional catalysts and chemical additives are used in the refining process [16].

Diesel can also be produced from organic feedstock, called biodiesel. It is currently relative expensive and has slightly lower gravimetric and volumetric energy density than MGO. Research in biodiesel-fuelled SOFCs is limited. It has been positively evaluated by Shiratori et al., externally and internally reformed [17]. However, it is expected that biodiesel will not be widely available since its production competes with food production [18, 19]. Another challenge is that the quality of the fuel depends much on the composition of the feedstock, with the risk of fuel impurities [20], for which fuel cells have low toleration [21].

Another possibility to produce diesel is using the Fischer-Tropsch process. First, a synthesis gas (syngas), which is a mixture of CO and H_2, is created. Following, the mixture is synthesised to a range of hydrocarbons. Finally, the hydrocarbons are upgraded to the final product. The syngas to liquid conversion (XTL) can originate from different feedstock, for instance, coal (CTL), natural gas (NTL) or biomass (BTL). By-products are water, carbon dioxide and heat. This fuel production process originated from situations where liquid fuel was needed, but oil-derived fuels were not easily accessible. The biggest drawback is that the efficiency of the production process is lower compared with for instance methanol production [22, 23, 20]

2.2. Hydrogen

Recently, the many initiatives by companies and governments demonstrate an increasing interest in hydrogen for marine applications. Hydrogen can be produced by reforming hydrocarbons or electrolysis of water. The first contributes to CO_2 emissions and the second requires much electric energy. Consequently, hydrogen is a clean fuel in its operation, but its production has negative environmental consequences [24].

The most common storage options for hydrogen are compressed or cryogenic. Cryogenic storage (at -253 °C) is currently the most energy-dense option, making it most suitable for marine applications and will be referred to as LH2 in this study [25]. Other methods, such as storage in chemical hydrides or adsorption materials are not further considered, for several reasons. Firstly, although these methods store hydrogen at high density, dehydrogenation is often challenging. Secondly, chemical hydrides are mainly attractive for single-use purposes, such as rockets. Thirdly, most of these storage methods are still in research phase [26]. The energy density of LH2 is the lowest compared with other alternative fuels. The cooling of hydrogen to cryogenic stage also requires much energy. Liquefied hydrogen is currently the most expensive alternative fuel for marine applications [27].

Although hydrogen can be used in SOFCs with satisfactory efficiency [28], it is not a straightforward choice. The main advantages of SOFC compared with LT-PEMFC are the possibility of internal reforming as well as its high tolerance to carbon monoxide (CO) and CO_2, which become obsolete for hydrogen. Moreover, CO is even used as fuel in SOFCs, further increasing efficiency. Due to the lower power density, the lower dynamic capability and the higher cost per kW of SOFC, LT-PEMFC would probably be the preferred option for hydrogen.

2.3. Natural gas

Natural gas (NG) is a combustible gas that can be found in porous rock is the earth's crust. Natural gas exists out of hydrocarbons of which methane (CH_4) has the highest concentration. The fuel contains small amounts of nitrogen, carbon dioxides and sulphur; its exact composition is place dependent [21]. Alternatively, natural gas can also be produced from bio-methane. Its most common storage method for marine applications is in cylindrical tanks at -162 °C, also called liquefied natural gas (LNG). The volumetric and gravimetric energy density for LNG storage is significantly lower than for diesel but higher than for hydrogen. Natural gas is increasingly being used in the marine industry, meaning its fuel infrastructure and production capacity are expanding [29, 30]. Initially, it was concluded that LNG fuelled marine engines can meet Tier III NO_X and SO_X emission regulations without emission abatement, as well as achieve significant CO_2 reduction [31]. However, more recently, methane slip in natural gas-fuelled engines is recognized as a serious concern due to its high global warming potential [32].

LNG spills vaporize quickly and do not harm aquatic life. As LNG vaporizes, the vapour is flammable when a source of ignition is present, but the auto-ignition temperature of methane (540 °C) is significantly higher than of diesel (312 °C). However, LNG can cause cryogenic burns to human skin. Nevertheless, LNG has the best track record in operational safety in the marine industry, and the fuel can be safely operated with proper ventilation strategies Woodward2014.

Most SOFC research and commercial available SOFC systems use natural gas as main fuel, and high efficiency has been demonstrated [33, 34, 35, 36]. Natural gas can be directly used in an SOFC after desulphurization and methane slip is negligible [35]. Biogas fuelled SOFC has shown comparable performance to hydrogen in terms of power production [37, 38].

2.4. Methanol

Methanol (MeOH) is an energy carrier and is widely applied in the chemical industry, resulting in a rather high production capacity and relatively low cost. The use of methanol-fuelled SOFCs slightly reduces onboard CO_2 emissions and largely reduces NO_X, SO_X and PM emissions, compared with MGO-fuelled combustion engines. However, methanol is mainly produced from natural gas, leading to significant CO_2 emissions during the production phase. Consequently, the CO_2 emissions are higher than for MGO [39].

Methanol can be stored in liquid form at room temperatures, omitting the need for large cylindrical tanks. Consequently, methanol can be stored at a higher energy density than gaseous fuels. This is enhanced since irregular ship volumes can be used to store fuel. Moreover, diesel infrastructure can be used for methanol after sleight adjustments [40].

Methanol dissolves in water, is biodegradable and is rated as non-toxic to aquatic organisms, making fuel spills less harmful than current marine fuels [41]. However, methanol is toxic to humans when internally ingested [42]. Compared to gasoline, methanol is less toxic and safer to handle [43, 44]. Few studies examined SOFC performance fuelled with methanol [6]. In contrast with natural gas, methanol has a relative low reforming temperature, making it more convenient to reform the fuel externally [45, 46]. Methanol-fuelled SOFC has not often been considered for marine applications (apart from the METHAPU project). Díaz-de Baldasano et al. [9] presented a conceptual design of an offshore platform supply vessel using methanol-fuelled SOFC. It was concluded that the hybrid fuel cell power plant does not limit the operational capabilities of the vessel and is technically and economically viable, taking into account the cost of the fuel cell system and the fuel .

2.5. Dimethyl ether

Dimethyl ether (DME) is a non-toxic, non-carcinogenic, biodegradable product with physical properties similar to liquefied petroleum gas (LPG). This makes it possible to use LPG storage and distribution infrastructure after minimal adjustments. DME is produced from catalytic methanol dehydration and is usually stored in liquid form at a pressure of five bar [47], having a higher volumetric and gravimetric energy density than methanol [48]. DME has a low production capacity, resulting in very low availability.

Last five years, DME has received increasing attention as a fuel for the marine industry, since it would lead to a reduction NO_X, SO_X and PM emissions [41, 49, 48, 6]. From a life cycle analysis, Semelsberger et al. [50] concluded that dimethyl ether produces the least amount of well-to-wheel greenhouse gas emissions compared with Fischer-Tropsch diesel, biodiesel, methanol and methane. After natural gas, dimethyl ether also showed the highest well-to-wheel efficiency for engines and fuel cells .

Above 700 °C, DME can be easily reformed to methane, carbon monoxide and hydrogen making it a convenient fuel for high-temperature fuel cells [48]. Consequently, SOFC systems directly fuelled with DME have been investigated; Murray et al. concluded a high power density [51]. One practical problem of directly supplying DME to SOFC is coke formation, but this can be suppressed by adding CO_2 to the fuel at high temperatures [48]. Sato et al. investigated the potential of steam reformed DME for SOFC. It was found that DME was easily reformed using a commercial catalyst, no coke was formed and nominal power level and electrical efficiency were reached using DME [52]. However, a lack of information on fuel storage, fuel processing and usage in SOFC makes it hard to evaluate DME as a fuel.

2.6. Ammonia

Ammonia (NH_3) is a chemical commodity that recently received more interest in the marine industry, since it can be used in modified engines and fuel cells. Because it contains no carbon, ammonia can be directly used in SOFC without the risk of CO poisoning or coke formation. Carbon dioxide and methane can not be emitted, because no carbon is present in the fuel. An ammonia-fuelled engine produces NO_X during the combustion, whereas an SOFC system fuelled by ammonia avoids most NO_X formation by producing N_2 as the main nitrogen-containing product [53].

Ammonia is used worldwide and is after sulphuric acid the most produced commodity chemical, ensuring a high technological readiness level (TRL) in production and distribution [54]. Ammonia is mostly produced from natural gas, which also contributes 80% of the cost. Consequently, the natural gas price drives the ammonia price [53].

Ammonia can be stored in its liquid form at -33 °C or at a pressure of 10 Bar [55]. Storage is characterized by moderate volumetric energy density, compared with the other discussed fuels. Moreover, Afif et al. reported that the storage- and transport cost of ammonia are much lower than for hydrogen [53]. An important drawback is its severe toxicity to humans and animals and its corrosivity [56].

Several investigations concluded that an SOFC running directly on ammonia shows similar performance as hydrogen [54]. Ammonia contains no sulphur, so a desulphuriser is not necessary for an ammonia-fuelled SOFC system.

3. Method

Many researchers compared alternative marine fuels by means of multi-criteria analysis (MCDA), using a wide range of criteria. Hansson et al. [4] evaluated LNG, methanol, hydrogen and vegetable oil using economic, operational, environmental and social criteria. By doing an extensive stakeholder analysis, they excluded the criteria infrastructure cost, bunkering time, eutrophication and public opinion, because

Table 2.: Advantages and disadvantages of alternative marine fuels for use in SOFCs.

Fuel	Advantages	Disadvantages
LNG	• Availability is increasing • No methane slip with fuel cells	• Significant onboard GHG emissions remain • Requires desulphurisation
Hydrogen	• Zero local emissions	• Currently low availability • Energy intensive production • Very expensive onboard storage system • Low stored energy density • Currently very high fuel cost
Diesel	• High availability • High energy density • High TRL • Developed infrastructure • Relative low cost	• High local GHG emissions • Requires desulphurisation • Cannot be used directly used in SOFCs • Complex reforming plant
Methanol	• Moderate energy density • Cheap fuel storage system	• Significant GHG emissions
DME	Further processed methanol: • Slightly higher power density • Nontoxic	• Expensive storage • Very low TRL as fuel
Ammonia	• Zero local carbon emissions • High production capacity • High TRL	• Significant NO_X emissions • Low stored energy density • Very toxic

they were rated as less important. [57] reviewed the used criteria in recent marine alternative fuel assessments. They suggested a minimum set of criteria, which included required technical modifications for the propulsion system, retrofit cost, fuel price, fuel availability, safety, and life cycle GHG emissions,.

The criteria in this study are selected based on the used criteria in earlier marine alternative fuel studies. When selecting criteria there is always a trade-off between the accuracy of the outcome versus the effort and data availability of the analysis. In this study, the criteria are defined from the ship perspective, or in other words which consequence the fuel has for the technical, economical, and environmental feasibility of the ship.

3.1. Discarded criteria

Some criteria were discarded because they were not relevant to this research or the availability of data was not sufficient to accurately evaluate them:

- *Conversion efficiency*
  The fuel type, as well as the conversion technology, has an impact on the electric efficiency. The electric conversion efficiency is a very relevant criterion for ships. For instance, a lower efficiency would lead to more fuel consumption, so a higher fuel cost, but also larger fuel tanks so a higher cost of the fuel storage system, and more emissions. Consequently, the conversion efficiency is not included as a separate criterion, but the other performance parameters will be compensated for

differences in power generation efficiency, for instance between diesel generators and SOFC systems.

- *Size and cost of fuel reforming plant*
  Generally, the cost of the SOFC system is dominated by the cost of the fuel cell stacks [58]. Although there are significant cost differences for the reforming plant between a hydrogen-fuelled LT-PEMFC system and a natural gas-fuelled LT-PEMFC system. Nevertheless, in SOFC most fuels can be reformed internally, meaning the cost differences in the reforming plant are less significant.

- *Maintenance cost*
  Insufficient data is available to distinguish maintenance costs for SOFC for different fuels. In general, it is estimated that maintenance cost is lower than for conventional (diesel gensets) power generation systems and is small compared to the purchase cost of the fuel cell system and the fuel cost [59].

- *Bunker speed*
  Although the bunker speed of the bunker fuel influences the operational feasibility for marine applications, at this stage of the research not enough data was available to quantitatively differentiate bunker speed for the considered fuels. Only the technological readiness of fuel bunkering is included in the criteria.

3.2. Selected criteria

To evaluate the fuel choice for SOFCs in marine applications, the criteria in Table 3. are defined. The criteria include technical, operational, economic, and environmental considerations. The decision criteria are established for marine applications in general.

Table 3.: Overview of selected decision criteria to evaluate marine fuels for SOFC systems.

Criterion	Type of criterion	Influenced by
Production capacity	Operational	Supply chain
Volumetric energy density	Technical	Storage system, conversion efficiency
Gravimetric energy density	Technical	Storage system, conversion efficiency
TRL	Technical	Fuel storage, fuel processing, interaction with fuel cell
Safety	Technical	Toxicity, flammability, explosivity, corrosivity
Fuel cost	Economical	Conversion efficiency, fuel production, fuel transport, fuel storage
Cost fuel storage system	Economical	Storage system, conversion efficiency
GHG emissions	Environmental	Fuel composition, conversion efficiency
NOx emissions	Environmental	Conversion process, conversion efficiency

4. Fuel evaluation for current situation

The different fuels are evaluated on the criteria of Table 3. in the following sections. The evaluation is based on scientific literature, supplier data, research projects and expert opinions of marine actors. For the fuel cost and emissions, different feedstocks are defined because of large discrepancies in the data. In this research, grey fuels are defined as produced from natural gas, blue fuels are produced from natural gas using carbon capture, and green fuels are produced with electrolysis using wind energy.

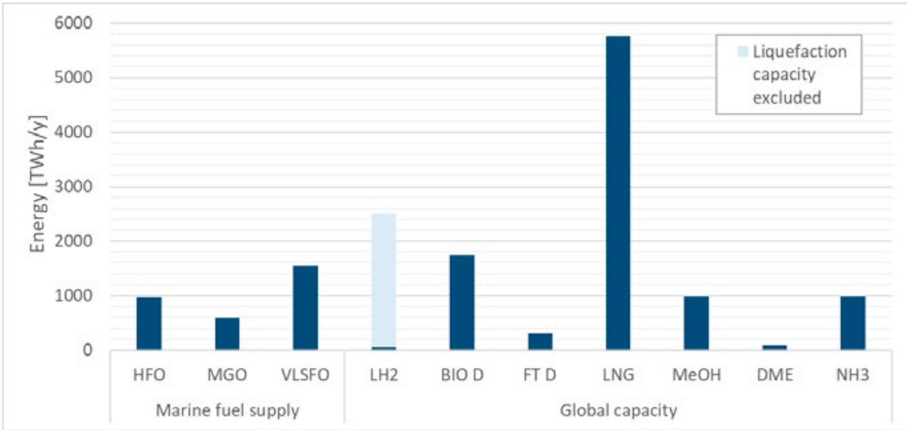


Figure 2.: Global supply of marine fuels and global capacity of considered alternative fuels in Tera Watthour per year. The light blue bar excludes liquefaction capacity. [60, 47, 61, 62, 63, 64, 65, 44, 66]

4.1. Production capacity

Since most of the alternative fuels are not yet used in the marine industry, it is senseless to compare the current use of marine fuels with the use of future fuels for the marine industry. To get an indication of the required scale up to apply the future fuels, the supply of marine fuels is compared with the total production capacity of the future fuels, see Figure 2.. Most alternative fuels have a comparable or higher global supply than the common marine fuels. However, the supply of DME and liquefied hydrogen is still very low and would require a massive scale-up for wide application in the marine industry. Nevertheless, it must be noted that the capacity of hydrogen production via electrolysis is rapidly growing, see Figure 3.. The capacity of Fischer-Tropsch Diesel is larger, but would still need significant scale up.

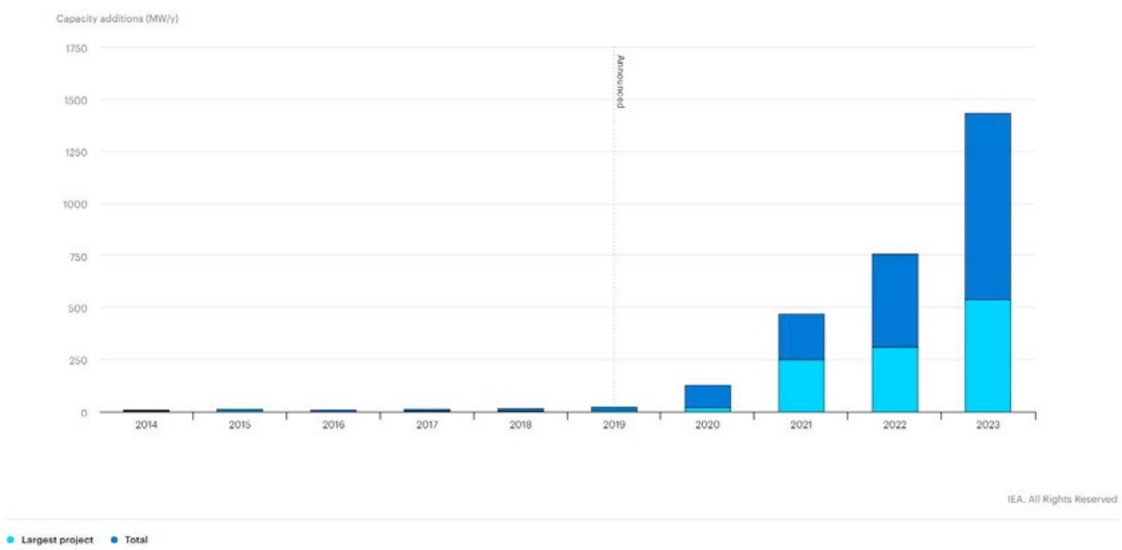
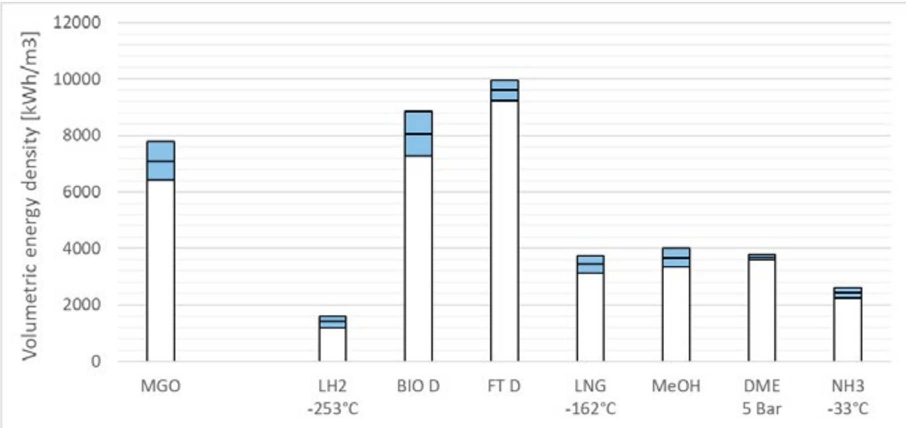
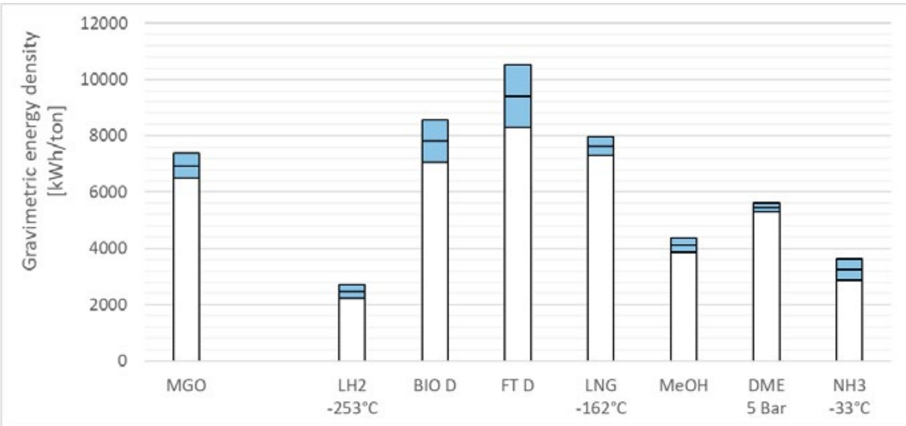


Figure 3.: Historical and announced global additions to hydrogen electrolysis capacity [67]



(a) Volumetric energy density



(b) Gravimetric energy density

Figure 4.: Energy density of future fuels including the onboard storage system of the concerned fuel. The benchmark (MGO) has been compensated for the efficiency difference between diesel generators (43%) and SOFC (55%). The blue bars show the data ranges found in literature [68, 39, 6, 69], research projects, and supplier specifications and is based on LHV.

4.2. Energy density

Current marine fuels (e.g., HFO, MGO) can be stored very energy densely. It is known that most of the alternative fuels struggle with a reduced energy density. Partly due to the lower energy density of the fuels and partly since some fuels must be stored in pressurized or cryogenic tanks, which reduces the effective energy density, because of the use of insulation and cylindrical tanks. The volumetric energy densities for onboard fuel storage are compared in Figure 4.(a). It is visible that MGO and biodiesel can be stored quite energy-dense. Fischer-Tropsch diesel can be stored at the highest energy density, since the composition of the diesel is very modifiable during the production process. Compared with the other future fuels, cryogenic hydrogen storage has a very low energy density. Consequently, much ship volume would be required to fit hydrogen.

Figure 4.(b) shows the comparison of the gravimetric energy density. Because of the high weight of the storage system, liquefied hydrogen is characterized by very low gravimetric energy density as well. LNG, biodiesel, and DME can be stored at a relatively good gravimetric energy density. For most ship types (with exception of high-speed crafts) the volumetric energy density is more critical than the gravimetric energy density.

4.3. Technological readiness level

To evaluate whether a future fuel is applicable in the near future, the fuels are rated based on their technological readiness for marine applications on a scale of one to five (where five represents the highest technological readiness). A distinction is made in readiness in fuel infrastructure (production and distribution), bunkering, onboard fuel handling (storage and supply to consumers), and the readiness to be used in SOFCs. The overview is shown in Table 4.

Table 4.: Technological readiness level of fuels in four different areas on a scale of one to five, where five represents the highest technological readiness [31, 70, 71, 72, 6, 73, 74]

Fuel	Fuel infrastructure	Fuel bunkering	Onboard fuel handling	Use in SOFCs
MGO	5	5	5	2
LH2	3	1	2	3
BIO D	3	5	4	1
FT D	3	5	4	2
LNG	4	3	4	5
MeOH	4	3	3	4
DME	1	1	1	1
NH3	4	1	2	3

4.3.1. Fuel infrastructure

Obviously, diesel infrastructure for marine applications is already in place. It has been stated that diesel infrastructure can be used for methanol after minor adjustments. LNG infrastructure has been increasing the last few years. Hydrogen, methanol and ammonia infrastructure is already large and can be extended when it must be used to fuel ships. DME infrastructure is very small (see also Figure 2.) and the knowledge about production storage and distribution is very limited.

4.3.2. Bunkering

The bunkering time is also very dependent on the successful operation of the cruise ship, especially since the energy density of the alternative fuels is lower than that of conventional fuels, it might be needed that the ship is refuelled more regularly, in order to limit cost and size of the fuel storage system. Sufficient bunkering speed is required to guarantee successful operation of the ship. Cryogenic fuels (LNG, LH2) often have a considerably lower fuelling speed. It is expected that the bunker speed of LH2 (which is currently done via trucks) is 10 times lower than diesel. Of course, the technological readiness for diesel bunkering is very high. Since several ships are currently operated on LNG and bunkering can be performed truck to ship or ship to ship, it has moderate bunkering TRL. For methanol bunkering, IGF codes have been established. The other fuels are barely used to bunker ships.

4.3.3. Onboard fuel handling

As was just explained only diesel and LNG have been widely applied to fuel ships. However, LH2, MeOH and NH3 are often applied in other industries, meaning there is much knowledge about storage, distribution, system control and safety regarding these fuels. This knowledge would still need to be transferred and converted to the marine industry, hence a moderate TRL for these fuels.

4.3.4. Use of fuel in SOFCs

Most SOFC research has been focused on an LNG-fuelled system. Moreover, all currently commercially available SOFC systems (Solid Power, BlueGen; Mitsubishi, Megamie; Bloom Energy, Energy Server; Hexis, Galileo) are designed for LNG. Most alternative fuels have been theoretically verified or simulated for SOFC systems, however, modifications to the reforming process and the system control are often necessary. Most studies report no difficulties for an ammonia-fuelled SOFC. Most alternative fuels have not been practically tested in a full-scale SOFC system, but methanol has been physically demonstrated.

4.4. Safety

Table 5. shows an overview of the danger classification of the future fuels, according to the Globally Harmonized System (GHS) of classification and Labelling of Chemicals. Fuels that are stored as compressed or cryogenic (LH2, LNG, DME, NH3) have additional risks due to a high operating pressure or low operating temperature. Consequently, well-ventilated spaces are necessary for safe operation. Although methanol and ammonia are often regarded as unsafe fuels due to their toxicity, it must be noted that conventional fuels also have significant safety and health risks. By GHS, methanol is not classified as corrosive. However, when mixed with water, methanol does become corrosive. Since water can stay in tanks and pipes after for instance cleaning, anti-corrosive materials are often used for methanol handling systems.

Table 5.: GHS classification for alternative marine fuels. According to the Globally Harmonized System of Classification and Labelling of Chemicals [75].

Fuel	**GHS02** Flammable	**GHS04** Gas	**GHS05** Corrosive	**GHS06** Toxic	**GHS07** Harmful	**GHS08** Health	**GHS09** Environment
	Highly flammable substance.	Compressed, liquefied or dissolved gas. May cause cryogenic burns.	Substance causes skin burns, eye damage, or destroys metals.	Toxic to humans when inhaled, swallowed or skin contact.	Substances that irritate skin and eyes or can cause dizziness.	Long-term health risks (mainly mutagenic or carcino-genic).	Substances that harm the aquatic environment directly or long-term.
MGO	✓				✓	✓	✓
LH2	✓	✓					
BIO D	✓				✓	✓	✓
FT D	✓				✓	✓	✓
LNG	✓	✓					
MeOH	✓			✓		✓	
DME	✓	✓			✓		
NH3	✓	✓	✓	✓			✓

4.5. Fuel price

The fuel cost is often a large contributor to the total cost of ownership. SOFC's high efficiency could save fuel cost and gives an opportunity to counteract the high capital cost of SOFC systems. However, some of the alternative fuels are currently very expensive, see Figure 5.. Especially blue and green hydrogen have high prices. LNG, MeOH and DME cost similar or even less compared with MGO (after compensating for the efficiency difference between DG and SOFC). Biodiesel and ammonia are more expensive than MGO. Fischer-Tropsch diesel has a large range of fuel cost, since there are many different possibilities in feedstock and production methods. It must be noted that over 95% of the currently produced hydrogen (Figure 2.) is grey hydrogen, although blue and green hydrogen plants are increasing in number and size.

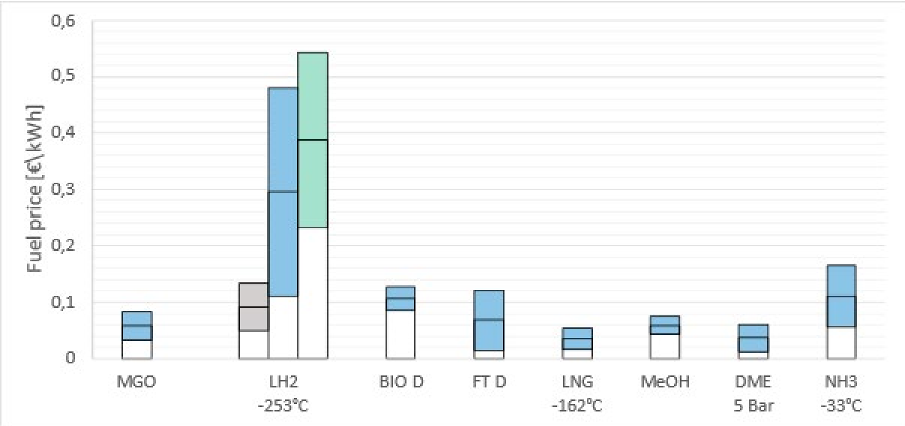


Figure 5.: Fuel prices of alternative marine fuels. Due to large discrepancies in the fuel price of hydrogen three categories are defined: grey hydrogen, blue hydrogen, and green hydrogen. The benchmark (MGO) has been compensated for the efficiency difference between diesel generators (43%) and SOFC (55%). The coloured bars show the data ranges found in literature [7, 76, 62, 47, 77, 78, 79, 80, 74], research projects, and supplier specifications. Data excludes the recent sharp rise in LNG price. Based on LHV of fuels.

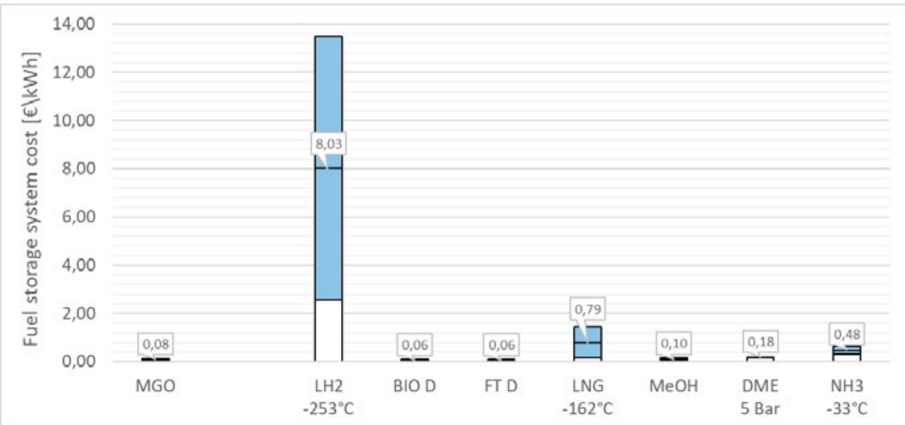


Figure 6.: Cost of fuel storage system for alternative marine fuels. Since not all bars are well visible, the median of the data is shown with labels. The benchmark (MGO) has been compensated for the efficiency difference between diesel generators (43%) and SOFC (55%). The blue bars show the data ranges found in literature [68, 81, 82, 78, 83, 84], research projects, and supplier specifications. Based on LHV of fuels.

4.6. Cost of fuel storage system

Generally in ship design, the cost of the fuel storage system is not a large economic driver, since conventional fuels are relatively easy to store. However, fuels like LH2, LNG and DME require cylindrical or spherical tanks, strong materials and good insulation since the fuels are stored under high pressure or at low temperature. These tanks are significantly more expensive than conventional fuel storage tanks, meaning this design driver should be taken into account. Figure 5 illustrates that especially hydrogen tanks result in a very large capital cost, which was also concluded by van Veldhuizen et al. [69]. Although the cost of LNG tanks is much lower than that of cryogenic hydrogen, it is still 10 times as expensive as MGO or biodiesel tanks. It must be noted that additional operational costs for energy to pressurize/cool the tanks and energy to recirculate the boil-off gas is not taken into account in the fuel storage system cost.

4.7. Emissions

Although life cycle analyses include many indicators for environmental impact, in this study, the scope is limited to the GHG emissions in the life cycle of the fuel. The NO_X, SO_X, and PM air pollutabts are not investigated for the different fuels because they are negligible for SOFCs with all considered fuels. Nevertheless, Figure 7. shows that the possible reduction in air pollutants when SOFC systems are applied. Figure 8. shows the GHG emissions for MGO-fuelled diesel generators, natural gas-fuelled gas generators and SOFCs for alternative fuels. Since some fuels have significant GHG emissions during the supply phase [85, 86] (i.e., extraction, production and storage and distribution) , the well-to-tank (WTT) emissions are also included. Fuel extraction, production, processing, purification, and storage are included in the WTT emissions. Emissions in the fuel transport phase are excluded because the data vary enormously per life cycle analysis, since it is very dependent on the production location, use location and transport method. The figure shows that all alternative marine fuels have lower ship emissions when using SOFCs than with MGO-fuelled diesel generators, mainly because of the higher conversion efficiency of S OFCs. However, when emissions in the supply chain are also included, the GHG emissions of grey hydrogen, biodiesel, and grey methanol are actually higher than MGO-fuelled diesel generators, which stresses the importance of including the life cycle emissions in such an analysis. Hydrogen can only reduce GHG emissions when blue or green hydrogen is used. SOFCs fuelled with Fischer-Tropsch diesel, LNG, DME or ammonia also reduce the GHG emissions over the life cycle of the fuel.

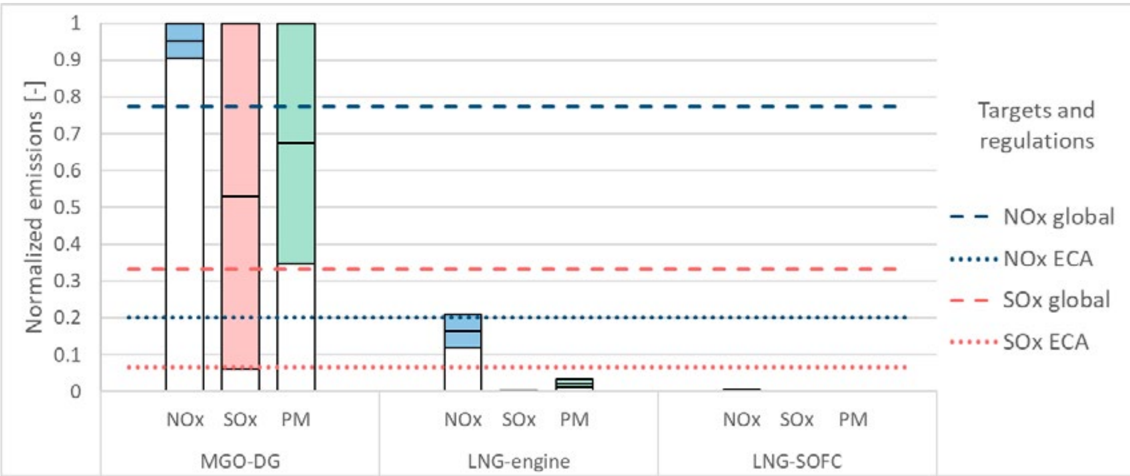


Figure 7.: NO_X, SO_X, and PM emissions from tank to wake.

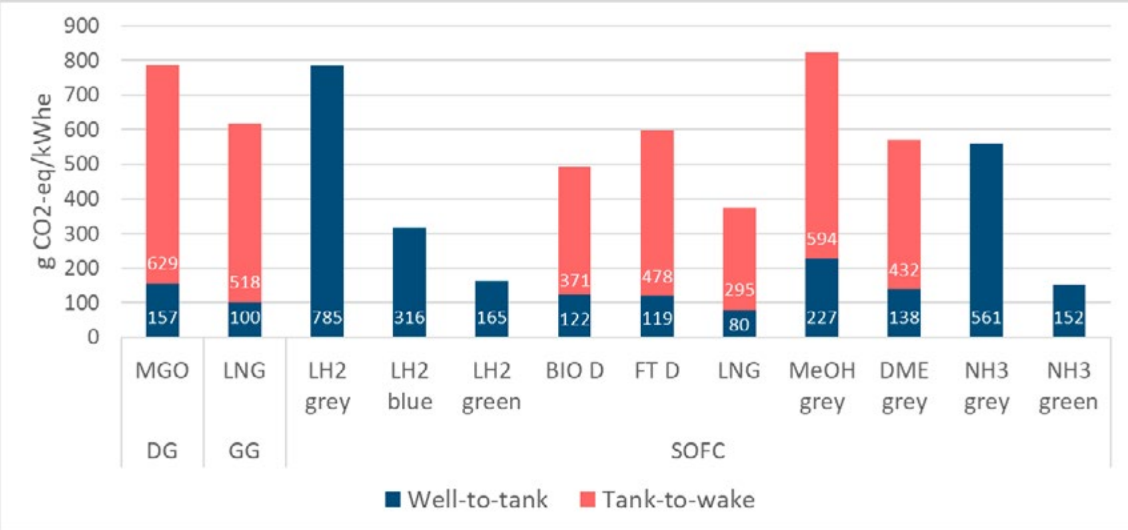


Figure 8.: Well-to-tank (WTT) and Tank-to-Wake (TTW) GHG emissions of future fuels. The WTT data includes production, liquefaction, storage and bunkering of fuels and excludes transportation of the fuel. The functional unit is kWh of onboard generated electricity and is based on LHV. The WTT data is based on life cycle analyses [87, 25, 88, 89, 90, 91, 92, 93, 39, 86, 85, 94] and the TTW emissions on supplier specifications and literature [95, 86, 96, 85].

5. Conclusion

This study evaluates the performance of alternative marine fuels for use in marine SOFC systems. The criteria are categorized in operational, technical, economical, and environmental parameters. The used parameters are production capacity, energy density of onboard storage, gravimetric energy density, technological readiness level, safety, fuel price, cost of fuel storage system, and life cycle emissions. The criteria are quantified and compared based on scientific literature, supplier data, research projects and expert opinions of marine actors.

5.1. Selected fuels

In the evaluation, no fuel performed best on all considered criteria. Consequently, no single best performing fuel can be concluded. Based on the evaluation several fuels are selected (Table 6.) which will be used for further research.

Table 6.: The fuels that are selected with the multi-criteria evaluation.

Short	**Fuel**	**Storage technique**
LNG	Liquified Natural Gas	Cryogenic (-162°C)
MeOH	Methanol	Liquid (Amb. T)
FT D	Fischer-Tropsch Diesel	Liquid (Amb. T)
NH3	Ammonia	Cryogenic (-33°C)
LH2	Hydrogen	Cryogenic (-253°C)

LNG is used to fuel most commercially available SOFC systems and performs moderately on energy density, cost and emissions. Moreover, natural gas is used in many industries and the production capacity is high. Safe operation in ships has already been proved.

Methanol scored very moderately on all criteria. It can be stored at a reasonable energy density and relatively low cost of the storage system. Since it is a commodity, scale-up for the marine industry is easier to realise and it is expected that existing infrastructure can be used after small modifications. The price of methanol is comparable to current fuels. All in all, this fuel leads to a solution that can be justified from a technical view as well as from an economical view. However, methanol should be produced from renewable sources, otherwise, it will not reduce GHG emissions, because the emissions in the production phase are significant.

Although Fischer-Tropsch diesel can not be operated without carbon emissions, it can be used carbon-neutral relatively easy. Fuel production has been invented a long time ago and is well-known. Since the substance is so similar to fossil types of diesels, it can be applied in the fuel infrastructure and in ships, which is a big advantage. It results in high energy density, low fuel storage cost and medium too high fuel price.

Although ammonia and its storage system are more expensive than methanol and DME, it is widely available, making it easier to expand its fuel infrastructure. Its energy density is quite low, but still much better than cryogenic stored hydrogen. Ammonia also results in much lower CO_2-eq emissions compared with the other options.

A long-haul hydrogen-fuelled ship would require such large storage tanks, which would have consequences on the dimensions or the operational performance of the ship. Moreover, the liquefaction capacity of hydrogen is currently very low. On top of that, the very high fuel- and storage cost would lead to an economically infeasible ship. Finally, although hydrogen is often considered as an ultra-low emission solution, this is only locally and significant emissions are apparent during the production process when produced from natural gas. However, the just-described context is merely based on the current situation. Green hydrogen production is increasing rapidly and there exist different technologies that can mitigate the storage disadvantages of hydrogen. Moreover, hydrogen has global political support. Because of its future prospects, hydrogen is still included in further research.

5.2. Future work

The presented analysis compared different fuels from a multi-criteria perspective. However, the fuel choice has major implications for an SOFC power plant. Some of the fuels require additional components such as reformers and evaporators, and the electrochemical reactions in the SOFC stack also depend on the used fuel. Consequently, the fuel choice influences the performance of the SOFC system, in terms of power density, electric efficiency, heat efficiency and specific cost. In our future work, the performance of marine SOFC power plants will be further investigated for the five fuels in Table 6.. An SOFC power plant will be designed with the required system components for the selected fuels, and thermodynamically modelled to analyse the electric and heat efficiency. The power density and specific cost of marine SOFC power plants will be compared for the different fuels in a bottom-up techno-economic analysis.

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