The maritime energy transition from a shipbuilder's perspective

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Synopsis

The maritime sector has thrived on using fossil hydrocarbon fuels, such as heavy fuel oil (HFO) and marine diesel oil (MDO). These fuels allowed vessels to carry large amounts of cargo over large distances, due to their high energy density. However, the climate objectives of the Paris agreement and the ever-tightening legislation regarding harmful emissions, such as nitrogen oxides (NO_X), sulphur oxides (SO_X) and particulate matter (PM) require the phasing out of fossil fuels.

The production of a renewable replacement for diesel is costly and requires a source of carbon. Therefore, renewable alternatives are most likely less energy dense than the diesel that is currently used. The transition to non-fossil energy carriers will thus be challenging for vessels that have a high power density, require a large autonomy, operate globally and/or have a challenging fuel logistics.

This paper presents a pathway to a carbon neutral maritime sector with nearly no harmful emissions. This transition calls for the development and implementation of clean and efficient energy conversion technologies on board vessels. In addition, efficient and cost effective production of alternative fuels is required, as well as the development of an adequate bunker infrastructure. Government policies to subsidise clean solutions and, if needed, tax emissions, need to be put in place to support these developments. These actions are preferably taken sooner rather than later, since vessels have a relatively long service life and, subsequently, a slow replacement rate.

Alternative energy carriers and drive system technologies are assessed based on their technology readiness and environmental impact. Each alternative is judged based on the total costs of ownership, as there is a trade-off between the technical developments, emission legislation, investment and the operational costs. The effect of government policy on the viability of the alternatives is also demonstrated.

Keywords: Energy transition, Alternative fuels, Zero emission vessels, Clean technologies, Life cycle performance assessment

1 Introduction

The energy transition is one of the greatest challenges of the 21st century. In 2017, fossil fuels supplied 81% of the world's primary energy demand and resulted in a CO_2 emission of 32.6 Gt [34]. The shipping sector produced 2.6% or 854 Mt of CO_2 emissions in 2017 [34], but without any changes the contribution of shipping will increase. The Paris Agreement aims to limit the global temperature rise caused by global warming to 1.5-2°C compared to the pre-industrial era [64]. Two possible CO_2 emission paths and their effect on the average temperature on Earth compared to the pre-industrial era are displayed in Figure 1. The current situation may result in a temperature increase of 3.2-5.4°C, while the Paris Agreement path limits the increase to 0.9-2.3°C. To achieve the Paris Agreement objective, a sharp decrease of CO_2 emissions is required.

The International Maritime Organisation (IMO) previously focussed on the reduction of harmful emissions e.g. sulphur oxides (SO_X), nitrogen oxides (NO_X) and particulate matter (PM). The shipping sector is not included in the Paris agreement, but nevertheless IMO adopted an initial strategy to reduce of greenhouse gas (GHG) emission from ships [36] in April 2018. This strategy aims to reduce GHG emissions of shipping with at least 50% in 2050 compared to the 2008 and aims to phase out GHG emissions entirely. The current IMO instruments to reduce CO_2 emissions from shipping are the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP). The EEDI covers about 85% of the CO_2 emissions from shipping and currently only applies to new built vessels [35]. Due to the long economic life of vessels on average 25 to 30 years [16], this results in a slow pickup of alternative (cleaner) fuels as fuel dependent retrofit costs are high.

Naval vessels are excluded from legislation related to GHG and harmful emissions. Despite this exemption, the Netherlands Ministry of Defence (MOD) aims to reduce the reliance on fossil fuels by 20% in 2030 and by 70%

Authors' Biographies

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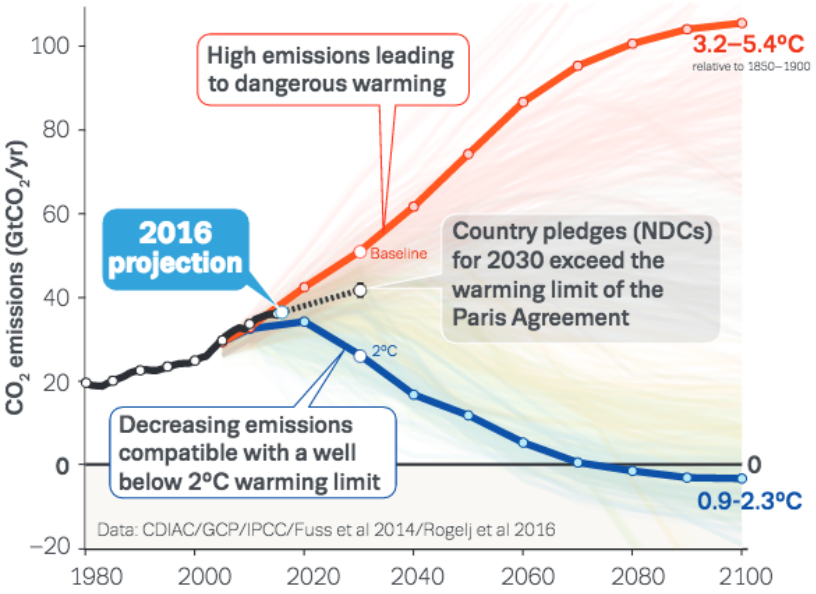

Figure 1: CO_2 emission scenarios up to 2100 [28].

in 2050 compared to 2010 [49]. The reasons for the Netherlands MOD to reduce the dependency on fossil fuels are mainly operational and a potential shortage of fossil fuels is among the main drivers [56]. NATO currently uses F-76 as its standard fuel for its non-nuclear powered ships [62]. The maritime energy transition may result in change of the standardised fuel used by the NATO naval fleet unless the maritime sector opts to change to renewable diesel as its primary fuel. However this would be the most expensive fuel option for the maritime sector which is generally focussed on reducing costs and likely to select the option that results in the lowest total cost of ownership [8, 32].

While a change away from F-76 has challenges, there may also be opportunities to improve the naval vessels and their combat skills with new fuels and consequently new drive systems. For example, nuclear power is already used to give submarines and aircraft carriers a virtually infinite range, and the German type 212 submarines use a hydrogen fuel cell system for air independent propulsion (AIP) [50]. Rapid developments of new fuels and drive systems in merchant shipping may eventually change naval ships as well, for example due to a change in the availability of F-76 or because of intrinsic advantages new drive systems in terms of fuel efficiency, reliability, infra-red signature and stealth [53, 65].

This paper discusses the effect of the maritime energy transition on the specific challenges and opportunities for naval vessels. Since naval vessels have different requirements than commercial vessels, a dedicated life cycle performance assessment (LCPA) method is required to determine the suitability of new fuels and prime movers for application. This method and how the most promising fuel and prime mover options score in the used key performance indicators (KPI)s will be discussed further below. The paper ends with some conclusions and recommendations for further research.

2 Future fuels and power plants

Emission reduction ambitions have motivated many investigations into new bunker fuels and drive systems for civil and merchant shipping. Emissions originate either from the fuel feedstock, such as the carbon dioxide and sulphur emissions from fossil fuels, or from the combustion process itself, which is for example the case for NO_X emissions [25]. In reality, the distinction is not so clear as specific emissions are affected by the fuel efficiency of the drive systems and the fuel efficiency in turn depends on the fuel used.

If there is anything we can distill from the vast research done on future fuels and drive systems, it is that there appears to be no silver bullet that can replace the existing bunker fuels and drive systems without compromising at least on at leat one performance indicator. For example, biodiesel can replace the existing F-76 fuel, but has different specification, is more expansive and not available everywhere. Similarly, gas turbines have low specific NO_X emissions and high power density, but are expensive and have a high specific fuel consumption [13].

2.1 Fuels

Liquefied natural gas (LNG) is currently becoming a more popular fuel for new-built vessels due to its green image and government subsidies as operating a dual fuel engine on natural gas results in a reduction of NO_X, SO_X and PM emission [24]. However, LNG is a fossil fuel and there are studies which state that its use results in a higher global warming potential (GWP) than using traditional marine diesel oil (MDO) when considering the well-to-propeller (WTP) emissions [24, 61]. In the long run, fuels from fossil sources will be replaced by fuels produced from a renewable feedstock. The feedstock can be either a form of biomass, a so-called biofuel, from renewable electricity, referred to as an e-fuel in this study, or a combination of the two.

Figure 2 shows the gravimetric and volumetric energy storage density for several fuel options including the required storage system. The energy density is independent of the fuels origin (fossil, biomass, e-fuel/renewable or a blend).

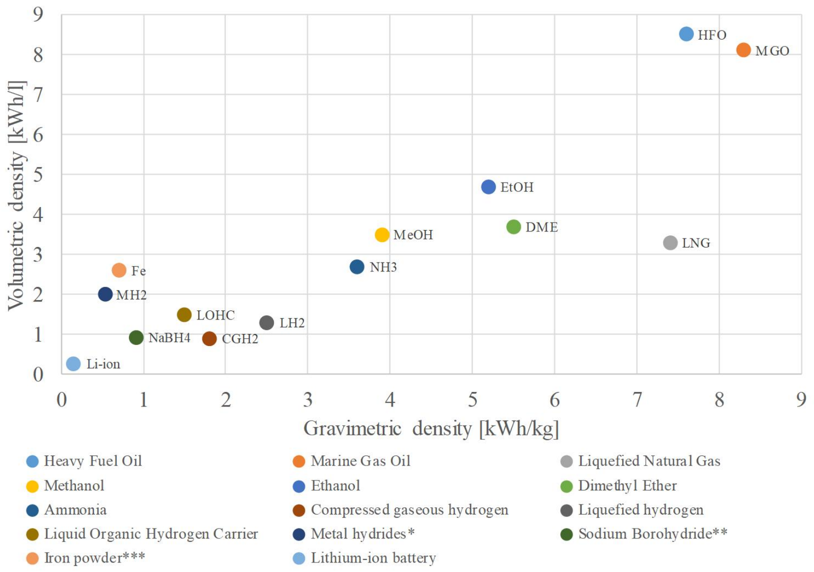

Figure 2: Volumetric and gravimetric energy density of logistic fuels including the tank system [46]. * Low temperature AB2, Ovonic, ** Fuel 30, wet spent fuel (reactor not included), *** Spent fuel (reactor not included)

2.1.1 Biofuels

Bio-diesel is commonly considered for application in ships, as it provides a drop-in solution that requires minimal changes to the fuel logistic and the existing power plant. However, the feedstock of current biofuels is limited, especially now biofuels produced from food crops are explicitly exempted in legislatory frameworks like the European Union (EU) Renewable Energy Directive (RED) [14]. Consequently, biofuels need to be produced from non-food biomass sources, such as waste streams, algae and seaweed [26].

There are two main routes used to produce biofuels from biomass. The first route uses fermentation and distillation to produce hydrogen, methane or alcohols like ethanol or butanol. These processes can be scaled relatively easily, but generally require specific feedstocks and microbes [11]. The other route uses thermochemical processing like pyrolysis and gasification. Pyrolysis yields an oil type solution that can be upgraded to diesel-like fuels [20]. Gasification yields a syngas mixture that is subsequently used to synthesise a fuel of choice, which has the advantage that the fuel production process is relatively independent of the biomass feedstock [6]. Methane, methanol and dimethyl ether (DME) can subsequently be synthesised with a relatively high efficiency [58].

The potential contribution of biomass as a renewable energy feedstock is unclear, but is estimated to vary from 10% to 30% [34]. The limiting factor for the biomass is the arable land required for its production, making it unlikely to become a dominant energy source, but a possible energy source for some niche markets [2].

2.1.2 E-fuels

Since biomass is expected to contribute to a maximum of 30% the future raw energy feedstock, achieving IMOs objective to reduce the total GHG emissions of shipping by 50% requires a shift to the less area intensive fuels. The area specific energy yield of renewable electricity, such as wind and solar, is substantially higher than biomass [52]. Therefore, renewable electricity may become the main energy feedstock in the future. Renewable electricity can, for example, be stored in batteries, but can also be used to produce hydrogen via electrolysis. Hydrogen is a well-known renewable energy carrier that can be used both in internal combustion engines and fuel cells. In addition, it can be combined with nitrogen to form ammonia or with carbon to produce hydrocarbon fuels [41]. This class of fuels goes by names like solar fuels, electro-fuels or e-fuels.

Brynolf et al. (2018) studied the production costs of several e-fuels, namely methane (CH_4), methanol (CH_3OH), dimethyl ether (DME), Fisher-Tropsch (FT)-liquids and gasoline. The production costs found for the reference scenario results in production costs ranging from 200 to 280 €/MWh in 2015 and from 160 to 210 €/MWh in 2030 [8]. Methane is the least expensive to produce followed by methanol, DME, gasoline and FT-diesel. The difference in costs between each fuel option is found to be small compared to the differences between the chosen high and low costs scenarios. Thus, it is yet unclear which fuel option will become dominant in the maritime sector.

Hydrogen is often considered the perfect long-term energy carrier, as no carbon is emitted on board. Renewable hydrogen is substantially more expensive than fossil today, but may become competitive within a decade by reduced electricity and electrolyser costs or emission regulation [27]. Hydrogen has a high specific energy but low specific volume, making storage challenging. The automotive standard is compressed storage at 350 and 700 bar, while cryogenic storage below 254 K is investigated for ships as well [44]. Alternatively, hydrogen can be stored in metal hydrides, which is for example applied on the German Type 212 submarines [50].

Ammonia (NH_3) unlike the hydrocarbon e-fuels does not require a CO_2 feedstock as well. Renewable or e-NH_3 may be produced by replacing the hydrogen currently produced by steam methane reforming (SMR) with hydrogen from a renewable source for the Haber-Bosch process. Ammonia can be stored as a liquid at moderate temperatures and pressures (-33.3°C or 10 bar). In addition, the Haber-Bosch process typically consumes less energy than hydrogen liquefaction, making it potentially cheaper than liquid hydrogen [3, 21]. The laminar flame velocity of NH_3 about 5 times lower than CH_4, making it difficult to combust in an Otto cycle engine [39]. Commercial application of NH_3 as a fuel is currently researched in several projects such as the EU ShipFC project in which the offshore support vessel Viking Energy will be retrofitted with a 2 MW NH_3 fuel cell [18].

2.2 Power plants

The change of bunker fuels affects the way power is produce on board ships. Compression ignition (or Diesel) engines and gas turbines provide a practically unrivalled solution for naval ships fuelled with F-76. Alternatives are not unseen on naval vessels, as Rankine cycles are deployed on vessels powered by nuclear energy and Stirling engines are used for AIP on submarines [51]. On merchant vessels, spark ignition and dual fuel engines have already been introduced to enable the use of LNG as a bunker fuel [45]. In addition, commercial shipping is looking actively at advanced internal combustion engines and fuel cells [65].

2.2.1 Internal combustion engines

Currently available maritime reciprocating internal combustion engines (ICE) operate according to the Diesel or the Otto cycle. The compression ignition (CI) and gas-diesel (GD) engines operate according to the Diesel cycle and the spark ignited (SI) and dual fuel (DF) engines operate according to the Otto cycle. CI engines require high Cetane number (CN) fuels such as diesel (40-55) and DME (55-60) as the ignition delay of low CN fuels is too long and prevents their use in this process [33]. NH_3 combustion in the CI process requires a compression ratio of 35 to achieve the required auto ignition temperature [15, 40].

Combusting low CN fuels such as natural gas (mostly CH_4), methanol, ethanol and liquefied petroleum gas (LPG) requires an external ignition source to start the combustion process [33]. This external source may be a spark (SI engine) or a flame from a pilot fuel (DF or GD engine). The main fuel of DF & SI engines is added in either the inlet port, the inlet receiver or before the compressor and compressed as a mixture with the air in the cylinder [23]. SI engines may be equipped with a pre-chamber with a richer air-fuel mixture to ensure combustion of the lean air-fuel mixtures in the main combustion chamber. Leaner mixtures result in a higher engine efficiency and lower NO_X emissions. The fuel injection in the inlet receiver or before the compressor results in fuel slip for engines with valve overlap. This slip may in case of some fuels such as methane negatively impact on the engine's GHG emissions. Most modern DF & SI engines inject the fuel in the inlet receiver and time injection based on the exhaust valve closure time to reduce fuel slip due to scavenging. However, fuel slip may still occur due to incomplete combustion caused by cylinder dead spots not reached by the flame front [23]. Both DF & SI engines operate based on the Otto cycle and thus require fuels with a high motor Octane number (MON) for knock stability and a flame speed capable of ensuring complete combustion in the available time. For highly toxic and/or corrosive fuels, a premixed air-fuel mixture may result in deposition of the fuel on the cylinder wall and other components possibly resulting in i.a. corrosion of engine components.

GD engines inject the main fuel at high pressure in the cylinder through the pilot fuel's combustion flame [23]. This results in a diesel like combustion and transient response as the combustion process is not limited by knocking and misfiring (occurring in a Otto cycle engine). The diesel like combustion does result in higher combustion related emissions such as NO_X. The pilot fuel is ignited by CI and thus requires a high CN. The GD engine can burn all liquids and gasses as the main fuel regardless of the CN, MON and flame velocity and it does not result in fuel deposition on the cylinder wall.

2.2.2 Fuel cells

Naval application of fuel cells has been investigated for decades for their high fuel efficiency and reduced infra-red and noise profile [53]. However, high cost, limited life time and low power density have so far hindered large scale adoption, both in civil and military applications. The increasingly stringent emission limits have recently accelerated the development of fuel cell technology, especially in automotive, combined heat and power and distributed power generation applications [59]. Continuous technology improvement and upscaled manufacturing have reduced cost, improved lifetime and reduced the size and weight of fuel cell systems considerably in recent years [66].

Three fuel cell types are anticipated to be promising for maritime applications: the low and high temperature polymer electrolyte membrane fuel cell (PEMFC) and the solid oxide fuel cell (SOFC). The LT-PEMFC operates around 65-80°C, has a high power density and good load-following capabilities. Therefore, it is heavily pursued by manufacturers in the automotive sector [48]. However, most LT-PEMFC products on the market require hydrogen as a fuel with a high purity. The HT-PEMFC operates at a slightly higher temperature around 140-160°C and has a better tolerance for fuel impurities. Products using methanol as a fuel are readily on the market, but power density and load-following capabilities are reduced compared to its low-temperature counterpart [5].

SOFCs operate at an even higher temperature, varying from 500°C up to 1000°C. The high operating temperature enables integration with internal fuel processing and waste heat recovery. Therefore, SOFC systems fuelled with natural gas are typically applied in combined heat and power applications, or provide electric power for businesses and data-centres in places where the natural gas grid is more reliable than the electricity grid [69]. Despite their fuel flexibility and electrical efficiencies up to 65%, SOFC products are still relatively expensive, large and heavy [22]. In addition, cold starts are slow and load-following is sluggish to prevent thermal overloading and fuel starvation [19, 47].

3 Naval Life Cycle Performance Analysis

The life cycle assessment (LCA) methodology based on ISO 14040 [38] is used to systematically analyse the cradle-to-grave environmental effects of products or services [31]. An LCPA is generally a simplified screening LCA with emphasis on KPI's important for a specific application. Within the FP7 EU-funded project JOULES, an LCPA method was developed to assess the economic and environmental performance of alternative vessel designs at an early design stage [67, 68, 60]. The net present value (NPV) was selected as the economic KPI. The environmental KPI's of this LCPA are the global warming potential (GWP), acidification potential (AP), aerosol formation potential (AFP), cumulative energy demand (CED) and eutrophication potential (EP). These are the most important environmental KPI's for applications which use large amounts of fossil fuels such as the transport sector [10, 9].

An LCPA can also focus more on the maintenance aspects of vessels and combine a screening LCA with life cycle costing (LCC) [30, 29]. The LCC methodology as defined in ISO 15686-5 [37] allows for comparative cost assessments over the entire vessel lifetime and includes all relevant economic factors [12]. This LCPA method uses more economic KPI's than only the NPV used in the JOULES LCPA and also includes the building cost, capital expenditure, operating expenditure and the maintenance and repair costs [29]. The environmental KPI's of this LCPA are limited to the EEDI and the NO_X and SO_X emissions (during operation), while in Gualeni et al. 2018, the CED and the PM emissions (during operation) are also included.

Neither of the LCPA methodologies discussed above is suitable for application on naval vessels as these are exempt from (most) environmental legislation and costs are generally not the limiting factor for choosing a fuel option for naval vessels. In this paragraph, the chosen KPI's for naval vessels will be discussed.

3.1 Naval key performance indicators

The operational effectiveness is the driving design characteristic of a naval vessel. The breakdown of this design characteristic involves:

- The performance of operational sensor, weapon and C4I-control tasks;
- The performance of the mobility function;
- The survivability of the vessel in the maritime theater threats;
- The performance of the auxiliary and support systems for these functions.

The survivability of naval vessels is one of the most important design characteristics and selecting suitable measures starts early in the design phase [42]. The design choices require compromises which may limit capabilities or future operations. The survivability of a naval vessel may be defined in the following terms [4, 42]:

- Susceptibility: This is the built-in ability of the vessel to avoid detection, identification and classification as a naval vessel and the ability to avoid a hit. Susceptibility determines the chance of a hit;
- Vulnerability: This is the built-in ability of the vessel to withstand damage and the chance/amount of damage if stricken. Vulnerability is determined by the damage probability if hit. Redundancy by the distribution of vital functions to each zone of the ship, and making them independent of each other, reduces the vulnerability of the ship and enhances the autonomy in it operations;
- Recoverability: This is the ability to return the vessel to normal operation after a hit. Recoverability is determined by the probability of repaired damage or redundancy and is usually defined related to the time available.

The vessel needs to be able to receive the fuel and handle it on board, therefore two fuel related KPI's are used, namely:

- Fuel availability: The likelihood the fuel will be available in the future;
- Fuel suitability: The consequences of the fuel choice on the vessel design and operation.

The total costs of vessel operation influence the political will to invest in new vessels and thus are also used in the LCPA in addition to survivability and fuel KPI's. In the following sections, each of these KPI's will be further explained and possible influences the fuel and drive system have will be quantified in more detail.

3.2 Offshore patrol vessel

The Holland class offshore patrol vessels (OPVs) of the Royal Dutch navy have been selected to demonstrate the effect of different fuel and prime mover combinations on the naval KPI's. These vessels are equipped with two MAN 12V28/33D diesel engines of 5460 kW each. Table 1 contains main size and power specifications of the Holland class vessels.

Table 1: Main specifications Holland class OPV [57]

Property	Value	Unit
Displacement	3,750	mt
Length	108.4	m
Beam	16	m
Draught	4.55	m
Speed	21.5	knots
Range (at 15 kt)	5,000	nm
Endurance	21	days
Total installed power	10920	kW

Table 2 shows a generalised and simplified annual operational profile with 5 activities for the OPV. The profile includes the time spent in each mode, the power the prime movers have to supply and the total energy supplied by the prime movers over the course of a year. The OPV is assumed to use shore power during the time it spends in port and is in maintenance. The mission activities of the OPV have been split in slow cruising, patrol at medium speed and high speed sailing. The prime movers have to supply 16980 MWh of energy over the course of a year.

Table 2: Estimated annual operational profile

Activity	Time [%]	Time [hrs.]	Power [%]	Power [kW]	Total energy required [MWh]
Slow cruising	10	876	20	2184	1912
Patrol	25	2190	45	4914	10762
High speed	5	438	90	9828	4305
Port	30	2628	0	0	0
Maintenance	30	2628	0	0	0
Total	100	8760	-	-	16980

The assumption has been made that the vessel concepts are equal in every way regarding improvements made on board to decrease power consumption. These improvements may include a more efficient heating, ventilation and air conditioning (HVAC) system, energy storage systems, shore power and waste heat recovery (WHR) systems. The following prime mover and fuel combinations have been selected for the analysis:

- CI (compression ignition) engines fuelled by synthetic FT-diesel (baseline);
- DF (dual fuel) engines using a FT diesel pilot and e-methane as the main fuel;
- GD (gad diesel) engines using a FT diesel pilot and e-methanol as the main fuel;
- SOFC fuelled by e-methane;
- SOFC fuelled by renewable ammonia;
- LT-PEMFC fuelled by liquefied hydrogen.

3.3 Survivability KPI analysis

Susceptibility: The main impact of configuration selections is on signatures. This is specifically addressed by a possible implementation of fuel cells. Fuel cell processes are solid state, so not combustion driven. This eliminates hot exhaust gasses (reaction product is water) and process acoustics (the fuel cell solid state process is silent). This is expected to radically reduce the thermal signature and the acoustic signature of the ship. Early verification of this consideration has of course been given by the application of fuel cells on board of conventional submarines.

Vulnerability: From the vulnerability perspective, the implementation of fuel cells will open the opportunity to support every zone of the naval vessel with its own power plant, providing the presence of fuel storage facilities in every zone. This will allow the much desired design principle to implement independent zones: if a zone is hit by a damage, the functions in the other zones may continue without being affected by the damaged zone. This is a design principle that is also attractive for e.g. cruise ships. However, fuel storage in multiple zones may increase the vessel's vulnerability as the chance of damage due to a hit increases.

Recoverability: Again here, fuel cells may have an advantage over internal combustion engines. The solid state operation (no moving parts, no wear, no tear) and the modular structure of a fuel cell system (stacks combines to modules and modules combine in systems) prevents the fuel cell system to a single point of failure, where the damage of one component of an internal combustion engine may result in a lot of cases into the breakdown of a complete engine. Furthermore, the stack- and modular characteristic of the fuel cell gives it a so-called graceful degradation: the failure of FC component reduces the availability of the system gradually. Finally, the solid-state process and modular structure of the fuel cell may drastically reduce the maintenance requirements for the energy system. This opens ship performance opportunities with a lesser dependence on maintenance and a smaller crew, which adds too to the recoverability of the naval vessel. Damaged fuel cell stacks, either by wear or combat, may be exchanged with spare stacks by the crew. Additionally, damaged sections may be supplied from undamaged sections, restoring the power and combat readiness of the vessel in a relatively shorter time than required for repairing damaged diesel engines.

3.4 Fuel KPI analysis

The future availability of a fuel is complex matter and there are a wide range of predictions available such as the World energy outlook of the International Energy Agency (IEA) [34] and DNV GL's Maritime Forecast to 2050 [17]. Since there is no conversion in these predictions, in this paper the likelihood of fuel availability will be based on the amount of primary energy required to power the vessel. The fuel suitability is judged based on the volume and mass required to store the fuel for the required 5,000 nm operational range.

Table 3 shows the prime mover efficiency and the total fuel energy consumption per year. In the calculations, the DF and GD engines use a FT-diesel pilot accounting for 2% of the fuel energy consumption. Figure 3 displays the annual energy consumption required to operate the OPV including the fuel production & processing losses and the energy required for transportation & distribution. An OPV with an ammonia fuelled SOFC requires about half of the primary energy of one powered by a CI engine fuelled with FT-diesel, the other concepts are distributed in-between. Powering the OPV with fuel cells makes more sense from a primary energy consumption perspective as these have a higher efficiency than combustion engines.

The application of fuel cell systems allows for the efficient implementation of a distributed power system. Fuel cells may be placed in spaces previously not considered suitable for other prime movers, such as diesel engines and gas turbines, due to their size or the location in the vessel. The efficiency of diesel engines and gas turbines decreases rapidly with decreasing power, while the efficiency of smaller fuel cells is only slightly influenced by a reduction of the size. Thus, for a diesel engine powered vessel, it makes sense to install fewer and larger engines. Fuel cells do not produce vibrations and noise, making it possible to place them close to crew quarters without decreasing the crew comfort. Distributing the power generations reduces the vulnerability of the vessel (as previously mentioned) and frees op space in the central machine room. This space may be used for among other things the storage of mission relevant equipment, thus increasing the military impact of the OPV or for fuel storage to increase the operational range of the vessel.

Table 3: Concept prime mover efficiency and yearly fuel energy requirement

Concept	Efficiency [%]	Total fuel energy [MWh]
CI-FT-diesel	42	40427
DF-methane	45	37732
GD-methanol	45	37732
SOFC-methane	60	28299
SOFC-ammonia	60	28299
LT-PEMFC-LH_2	55	30872

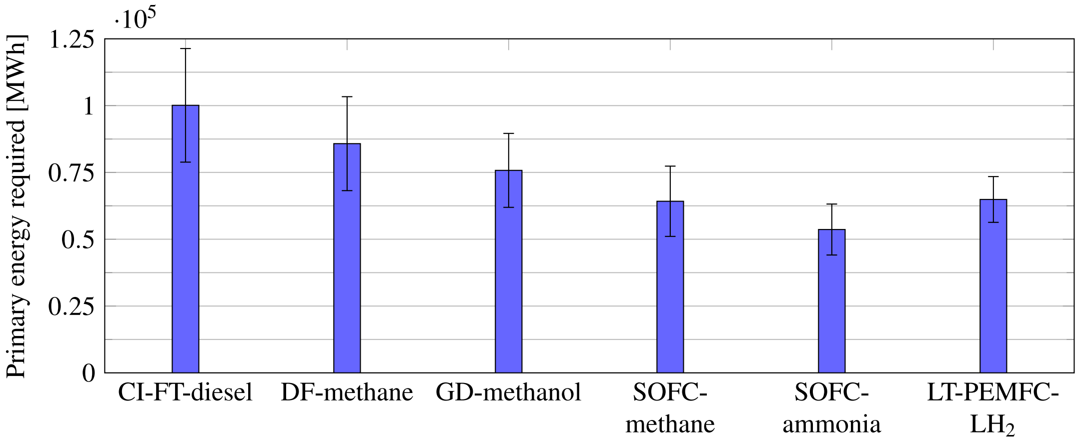

Figure 3: Estimated annual primary energy consumption of OPV

The suitability of the fuel for application on the vessel includes the mass and volume taken up by the prime movers and the fuel required for the 5,000 nm operating range (at 15 knots) as given in the specifications (Table 1). The OPV is estimated to require 4914 kW (Patrol load from Table 2) to sail at 15 kt, resulting in a total required energy of 1638 MWh.

The prime mover mass and volume are calculated with the specific gravimetric and volumetric power density of prime movers as given in Table 4 and the installed power (Table 1). Figures 4 & 5 display the total mass and volume of the prime mover, fuel and storage system. The mass and volume of the fuel and the storage system are based on the data from Figure 2 and the prime mover efficiency (Table 3).

The LT-PEMFC-LH_2 concept has the lowest prime mover and fuel mass, however the cryogenic storage system makes this the heaviest option. Cryogenic storage systems increase the required mass and volume significantly, especially in the case of LH_2 due to the extremely low temperature (20K). The SOFC-methane concept has the lowest overall mass requirement followed by the CI-FT-diesel and the DF-methane concept. The FT-diesel concept requires the least volume due the high volumetric energy density and easy storage of diesel fuels. The next best options, the SOFC-methane and SOFC-ammonia require about 72% and 77% more space respectively. While not all vessels are mass and/or volume limited in their design, both are generally important as they influence ship stability, acceleration and manoeuvrability of the vessel. In addition, a lower mass and/or volume of the fuel and prime mover system allows ship designers more freedom in the vessel design.

Table 4: Specific gravimetric and volumetric power density of the prime mover options

Concept	Specific gravimetric power density [W/kg]	Specific volumetric power density [W/l]
CI-FT-diesel	66.80	49.40
DF-methane	60.10	42.88
GD-methanol	60.10	42.88
SOFC-methane	62.7	28.5
SOFC-ammonia	104.5	47.5
LT-PEMFC-LH_2	229	63

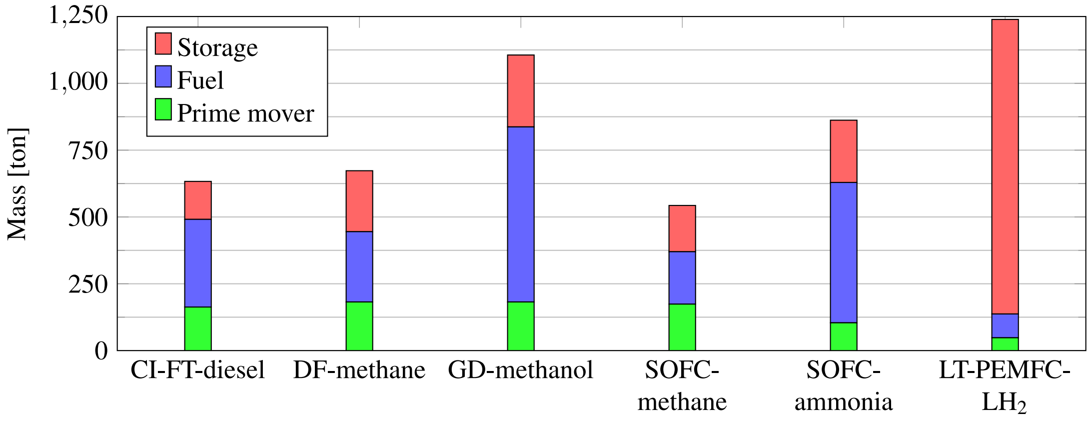

Figure 4: Mass of the prime mover, the fuel and the fuel storage system

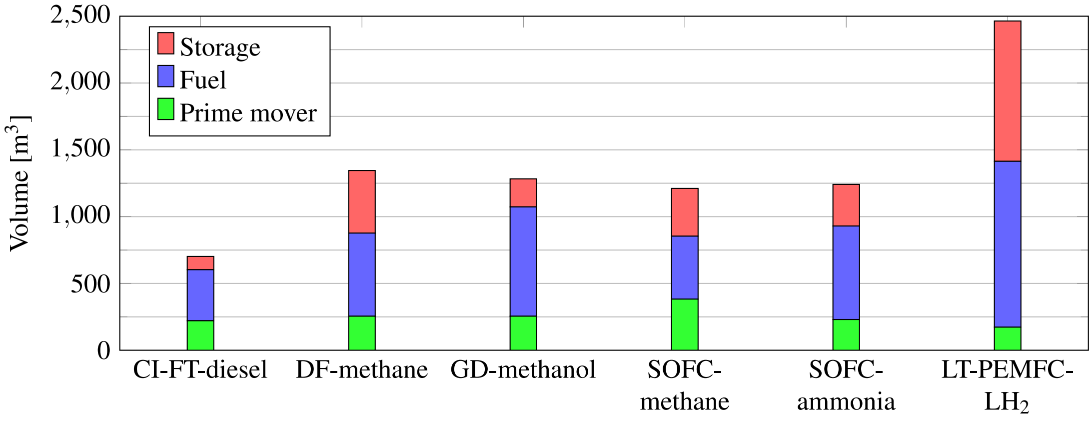

Figure 5: Volume of the prime mover, the fuel and the fuel storage system

3.5 Economic KPI analysis

New energy carriers and power and propulsion systems affect both the capital expenditure (CAPEX) and operational expenditure (OPEX) of naval vessels like an OPV. Advanced combustion engines, (gaseous) fuel storage and handling systems and corresponding safety requirements, such as gas sensors and double-walled piping, increase the cost of a vessel's power and propulsion system [55]. Nowadays, fuel cell systems are especially expensive. LT-PEMFC prices are generally over 1000 €/kW and SOFC over 5000 €/kW [65]. However, manufacturers expect that these prices might be reduced with an order of magnitude through large scale manufacturing, which would be competitive [1, 54].

The OPEX is dominated by fuel costs and maintenance cost. The fuel production costs are used to estimate the annual fuel costs of the OPV and are calculated based on the fuel energy consumption as given in Table 3 and the 2030 reference fuel prices from Brynolf et al. [8]. Figure 6 shows that the SOFC-ammonia concept has the lowest annual fuel production cost followed by the LT-PEMFC-LH$_2$ and SOFC-methane concepts. This result suggests that a trade-off exists between the lower CAPEX for conventional prime movers fuelled with FT-diesel and lower OPEX of advanced power and propulsion systems with gaseous fuels. This demonstrates the importance of a comprehensive LCA, taking into account investment, fuel and maintenance costs.

The solid state nature of PEMFCs and SOFCs implies they have the tendency to degrade rather than fail. Therefore, maintenance requirements may be substantially reduced by adopting fuel cell systems. However, the fuel cell stack requires occasional replacement, which costs are typically estimated around half the original investment cost. Target stack life times for heavy duty LT-PEMFCs are typically around 25 kh, SOFC manufacturers are generally aiming for stack lifetimes of at least 40 kh [43, 63]. Next to stack replacement, maintenance may be limited to inspection of rotating equipment (e.g. pumps and blowers) and calibration of safety sensors.

4 Conclusions and recommendations

The Naval Life Cycle Performance Assessment criteria as discussed in this paper give an holistic overview of emission reduction capabilities of a ship propulsion design, including trade-offs in performance and costs.

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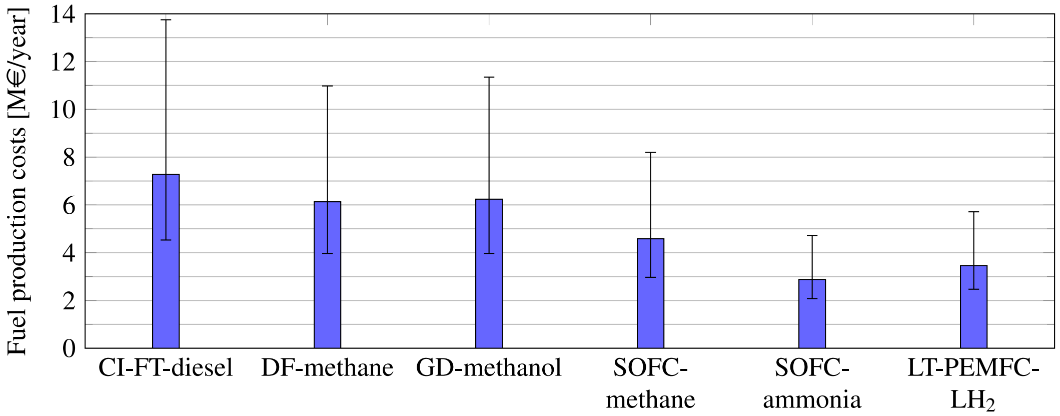

Figure 6: Annual fuel production costs of the OPV in 2030

Although naval vessels may have other design priorities, the LCPA-related conversion to other propulsion configurations may have a very positive impact on the operational performance of naval ships.

The application of alternative fuels in combination with fuel cells may include very significant reductions of thermal infrared and acoustic emissions, an enhanced design opportunity to design zones with independent energy supply, a higher reliability (no single point of failure, graceful degradation of power supply) and an enhancement in autonomy of system operation because of a lower level of maintenance requirements en engineering services.

Fuel cell systems allow for the application of distributed power systems, reducing the vessel's vulnerability. Fuel cell stacks can be exchanged/replaced more easily than diesel engines, improving the vessel's recoverability. Distributing the power generation through the ship will allow vessel designers to optimize the design and thus improve the operational capabilities of the vessel.

It is recommended that this Dual Use technology is being adopted by Naval Designers to contribute to the required disruptive design features of future combat ships.

References

[1] Abed Alaswad, Ahmad Baroutaji, Hussam Achour, James Carton, Ahmed Al Makky, and Abdul-Ghani Olabi. Developments in fuel cell technologies in the transport sector. *International Journal of Hydrogen Energy*, 41(37):16499–16508, 2016.

[2] C.J. Andrews, L. Dewey-Mattia, J.M. Schechtman, and M. Mayr. *Alternative Energy Sources and Land Use*. Lincoln Institute of Land Policy, 2011.

[3] CR Baker and RL Shaner. A study of the efficiency of hydrogen liquefaction. *International Journal of Hydrogen Energy*, 3(3):321–334, 1978.

[4] R.E. Ball and C.N. Calvano. Establishing the fundamentals of a surface ship survivability design discipline. *Naval Engineers Journal*, 106:71–74, 1994.

[5] Steve Barrett. Serenergy powers first german methanol fuel cell vessel, 2017.

[6] Niclas S Bentsen and Ian M Møller. Solar energy conserved in biomass: Sustainable bioenergy use and reduction of land use change. *Renewable and Sustainable Energy Reviews*, 71:954–958, 2017.

[7] E.A. Bouman, E. Lindstad, A.I. Rialland, and A.H. Strømman. State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping – a review. *Transportation Research Part D*, 52:408–421, 2017.

[8] S. Brynolf, M. Taljegard, M. Grahn, and J. Hansson. Electrofuels for the transport sector: A review of production costs. *Renewable and Sustainable Energy Reviews*, 81:1887–1905, 2018.

[9] M.B.G. Castro, M.J. Holtkamp, P.M. Vercruijsse, E.C. van der Blom, and D. van Woerden. Using life cycle analysis methodology to assess the sustainability of dredging equipment and its manufacturing process. In *Proceesings of the CEDA Dredging Days 2011*.

[10] M.B.G. Castro, J.A.M. Remmerswaal, and M.A. Reuter. Life cycle impact assessment of an average passenger vehicle in the netherlands. *The International Journal of Life Cycle Assessment*, 8:297–304, 2003.

[11] Monika Choudhary, Sunanda Joshi, Priya Singh, and Nidhi Srivastava. Biofuel production from lignocellulosic biomass: Introduction and metabolic engineering for fermentation scale-up. In *Genetic and Metabolic Engineering for Improved Biofuel Production from Lignocellulosic Biomass*, pages 1–12. Elsevier, 2020.

[12] Davis Langdon Management Consulting. Literature review of life cycle costing (lcc) and life cycle assessment (lca).

[13] Sanjay M Correa. A review of nox formation under gas-turbine combustion conditions. *Combustion science and technology*, 87(1-6):329–362, 1993.

[14] Reinier De Man and Laura German. Certifying the sustainability of biofuels: promise and reality. *Energy Policy*, 109:871–883, 2017.

[15] P. Dimitriou and R. Javaid. A review of ammonia as a compression ignition engine fuel. *International Journal of Hydrogen Energy*, 45:7098–7118, 2020.

[16] O. Dinu and A.M. Ilie. Maritime vessel obsolescence, life cycle cost and design service life. *IOP Conference Series: Materials Science and Engineering*, 95:012067, 2015.

[17] Ø. Endresen, M.S. Eide, and T. Longva. Maritime forecast to 2050. energy transition outlook 2019.

[18] FCH Europe. Major fch ju funded project will install the world's first ammonia-powered fuel cell on a vessel.

[19] Mahshid Fardadi, Dustin F McLarty, and Faryar Jabbari. Investigation of thermal control for different sofc flow geometries. *Applied Energy*, 178:43–55, 2016.

[20] Javier Fermoso, Patricia Pizarro, Juan M Coronado, and David P Serrano. Advanced biofuels production by upgrading of pyrolysis bio-oil. *Wiley Interdisciplinary Reviews: Energy and Environment*, 6(4):e245, 2017.

[21] D Frattini, G Cinti, G Bidini, Umberto Desideri, R Cioffi, and E Jannelli. A system approach in energy evaluation of different renewable energies sources integration in ammonia production plants. *Renewable Energy*, 99:472–482, 2016.

[22] Marta Gandiglio, Andrea Lanzini, and Massimo Santarelli. Large stationary solid oxide fuel cell (sofc) power plants. In *Modeling, Design, Construction, and Operation of Power Generators with Solid Oxide Fuel Cells*, pages 233–261. Springer, 2018.

[23] I. Georgescu, D. Stapersma, L.M. Nerheim, and B.T.W. Mestemaker. Characterisation of large gas and dual-fuel engines. *MTZ industrial*, 6:64–71, 2016.

[24] P. Gilbert, C. Walsh, M. Traut, U. Kesieme, K. Pazouki, and A. Murphy. Assessment of full life-cycle air emissions of alternative shipping fuels. *Journal of Cleaner Production*, 172:855–866, 2018.

[25] Paul Gilbert, Conor Walsh, Michael Traut, Uchenna Kesieme, Kayvan Pazouki, and Alan Murphy. Assessment of full life-cycle air emissions of alternative shipping fuels. *Journal of cleaner production*, 172:855–866, 2018.

[26] S. Gillman. Seaweed-powered trucks - hope or hype?

[27] Gunther Glenk and Stefan Reichelstein. Economics of converting renewable power to hydrogen. *Nature Energy*, 4(3):216–222, 2019.

[28] Global Carbon Project. Global carbon budget 2016, 2016.

[29] P. Gualeni, G. Flore, M. Maggioncalda, and G. Marsano. Life cycle performance assessment tool development and application with a focus on maintenance aspects. *Journal of Marine Science and Engineering*, 7:280, 2019.

[30] P. Gualeni and M. Maggioncalda. Life cycle ship performance assessment (lcpa): A blended formulation between costs and environmental aspects for early design stage. *International Shipbuilding Progress*, 65:127–147, 2018.

[31] J.B. Guinée, M. Gorrée, R. Heijungs, G. Huppes, R. Kleijn, A. de Koning, L. van Oers, A.W. Sleeswijk, S. Suh, H.A.U. de Haes, H. de Bruijn, R. van Duin, and M.A.J. Huijbregts. Handbook on life cycle assessment. operational guide to the iso standards. part iii: Scientific background. *The International Journal of Life Cycle Assessment*, 7(311), 2002.

[32] Severin Hänggi, Philipp Elbert, Thomas Bütler, Urs Cabalzar, Sinan Teske, Christian Bach, and Christopher Onder. A review of synthetic fuels for passenger vehicles. *Energy Reports*, 5:555–569, 2019.

[33] J.B. Heywood. *Internal combustion engine fundamentals*. 1988.

[34] International Energy Agency (IEA). *World Energy Outlook 2018*. 2018.

[35] International Maritime Organization (IMO). Amendments to the annex of the protocol of 1997 to amend the international convention for the prevention of pollution from ships, 1973, as modified by the protocol of 1978 relating thereto: Inclusion of regulations on energy efficiency for ships in MARPOL ANNEX VI, 2011.

[36] International Maritime Organization (IMO). Initial IMO strategy on reduction of GHG emissions from ships, 2018.

[37] International Standards Organization (ISO). *International Standard ISO 15686-5: Buildings and constructed assets – Service-life planning – Life cycle costing*, 2006.

[38] International Standards Organization (ISO). *International Standard ISO 14040: Environmental Management – Life Cycle Assessment – Requirements and Guidelines*, 2008.

[39] H. Kobayashi, A. Hayakawa, K.D.K.A. Somarathne, and E.C. Okafor. Science and technology of ammonia combustion. *Proceedings of the Combustion Institute*, 37:109–133.

[40] D. Lee, H.H. Song, H. Min, and H. Park. Development of new combustion strategy for internal combustion engine fueled by pure ammonia. In AIChE, editor, *2017 AIChE Annual Meeting*.

[41] Mason Scott Lester, Rasmus Bramstoft, and Marie Münster. Analysis on electrofuels in future energy systems: A 2050 case study. *Energy*, page 117408, 2020.

[42] H. Liwng and H. Jonsson. Comparison between different survivability measures on a generic frigate. *International Journal Maritime Engineering*, 157(A2):325, 2015.

[43] Natalia Macauley, Mark Watson, Michael Lauritzen, Shanna Knights, G Gary Wang, and Erik Kjeang. Empirical membrane lifetime model for heavy duty fuel cell systems. *Journal of Power Sources*, 336:240–250, 2016.

[44] K Maekawa, M Takeda, T Hamaura, K Suzuki, Y Miyake, Y Matsuno, S Fujikawa, and H Kumakura. First experiment on liquid hydrogen transportation by ship inside osaka bay. In *IOP Conference Series: Materials Science and Engineering*, volume 278, page 012066. IOP Publishing, 2017.

[45] BTW Mestemaker, MB Goncalves Castro, HN van den Heuvel, and K Visser. Dynamic simulation of a vessel drive system with dual fuel engines and energy storage. *Energy*, 194:116792, 2020.

[46] B.T.W. Mestemaker, H.N. van den Heuvel, and M.B. Gonçalves Castro. Designing the zero emission vessels of the future: Technologic, economic and environmental aspects. *International Shipbuilding Progress*, 67:5–31, 2020.

[47] Marko Nerat. Modeling and analysis of short-period transient response of a single, planar, anode supported, solid oxide fuel cell during load variations. *Energy*, 138:728–738, 2017.

[48] Yasuhiro Nonobe. Development of the fuel cell vehicle mirai. *IEEJ Transactions on Electrical and Electronic Engineering*, 12(1):5–9, 2017.

[49] Netherlands Ministry of Defence. Operational energy strategy, 2015.

[50] Angela Psoma and Gunter Sattler. Fuel cell systems for submarines: from the first idea to serial production. *Journal of Power Sources*, 106(1-2):381–383, 2002.

[51] Michael Raska. Diesel-electric submarine modernization in asia: The role of air-independent propulsion systems. In *Emerging Critical Technologies and Security in the Asia-Pacific*, pages 91–106. Springer, 2016.

[52] Pablo Ruiz, Wouter Nijs, Dalius Tarvydas, A Sgobbi, Andreas Zucker, R Pilli, R Jonsson, A Camia, Christine Thiel, Carsten Hoyer-Klick, et al. Enspreso-an open, eu-28 wide, transparent and coherent database of wind, solar and biomass energy potentials. *Energy Strategy Reviews*, 26:100379, 2019.

[53] Gunter Sattler. Fuel cells going on-board. *Journal of power sources*, 86(1-2):61–67, 2000.

[54] R Scataglini, M Wei, A Mayyas, SH Chan, T Lipman, and M Santarelli. A direct manufacturing cost model for solid-oxide fuel cell stacks. *Fuel Cells*, 17(6):825–842, 2017.

[55] O Schinas and M Butler. Feasibility and commercial considerations of lng-fueled ships. *Ocean Engineering*, 122:84–96, 2016.

[56] Paul Schulten, Rintze Geertsma, and Klaas Visser. Energy as a weapon, part ii. In IMarEST, editor, *Engine As A Weapon International Symposium (EAAW VII) Symposium Proceedings*.

[57] Damen Schelde Naval Shipbuilding. Patrol ship "holland class".

[58] Vineet Singh Sikarwar, Ming Zhao, Paul S Fennell, Nilay Shah, and Edward J Anthony. Progress in biofuel production from gasification. *Progress in Energy and Combustion Science*, 61:189–248, 2017.

[59] Carlo Strazza, Adriana Del Borghi, Paola Costamagna, Michela Gallo, Emma Brignole, and Paola Girdinio. Life cycle assessment and life cycle costing of a sofc system for distributed power generation. *Energy Conversion and Management*, 100:64–77, 2015.

[60] C. Thiem, R. Nagel, J. Ellis, and S. Hänninen. JOULES technical report D21.1 cost models and LCA.

[61] H. Thomson, J.J. Corbett, and J.J. Winebrake. Natural gas as a marine fuel. *Energy Policy*, 87:153–167, 2015.

[62] J.D. Tosh, D.S. Moulton, and C.A. Moses. Navy fuel specification standardization.

[63] Hengyong Tu and Ulrich Stimming. Advances, aging mechanisms and lifetime in solid-oxide fuel cells. *Journal of power sources*, 127(1-2):284–293, 2004.

[64] United Nations Framework Convention on Climate Change (UNFCCC). What is the Paris agreement?

[65] L Van Biert, M Godjevac, K Visser, and PV Aravind. A review of fuel cell systems for maritime applications. *Journal of Power Sources*, 327:345–364, 2016.

[66] Guangjin Wang, Yi Yu, Hai Liu, Chunli Gong, Sheng Wen, Xiaohua Wang, and Zhengkai Tu. Progress on design and development of polymer electrolyte membrane fuel cell systems for vehicle applications: A review. *Fuel Processing Technology*, 179:203–228, 2018.

[67] S. Wurst. Joules technical report r22-1. guidelines for lcpa software tool.

[68] S. Wurst, R. Nagel, S. Vatanen, A. Liebich, and J. Ellis. D 22.1 – lcpa-tool incl. lcpa and lca description.

[69] Li Zhao, Jacob Brouwer, Sean James, Eric Peterson, Di Wang, and Jie Liu. Fuel cell powered data centers: In-rack dc generation. *ECS Transactions*, 71(1):131, 2016.