Solid Oxide Fuel Cells for Marine Applications

van Veldhuizen, B.N.; van Biert, L.; Aravind, P.V.; Visser, K.

DOI
10.1155/2023/5163448

Publication date
2023

Document Version
Final published version

Published in
International Journal of Energy Research

Hindawi
International Journal of Energy Research
Volume 2023, Article ID 5163448, 35 pages
https://doi.org/10.1155/2023/5163448

Review Article

Solid Oxide Fuel Cells for Marine Applications

Berend van Veldhuizen,[1] **Lindert van Biert**,[1] **Purushothaman Vellayani Aravind**,[2] **and Klaas Visser**[1]

[1]*Department Ship Design, Production and Operations, Delft University of Technology, Mekelweg 5, 2628 CD Delft, Netherlands*
[2]*Energy Conversion, Energy and Sustainability Research Institute, University of Groningen, Nijenborgh 6, 9747 AG Groningen, Netherlands*

Correspondence should be addressed to Berend van Veldhuizen; berendvv96@gmail.com

Received 6 October 2022; Revised 20 December 2022; Accepted 27 April 2023; Published 30 May 2023

Academic Editor: Arun Thirumurugan

The marine industry must reduce emissions to comply with recent and future regulations. Solid oxide fuel cells (SOFCs) are seen as a promising option for efficient power generation on ships with reduced emissions. However, it is unclear how the devices can be integrated and how this affects the operation of the ship economically and environmentally. This paper reviews studies that consider SOFC for marine applications. First, this article discusses noteworthy developments in SOFC systems, including power plant options and fuel possibilities. Next, it presents the design drivers for a marine power plant and explores how an SOFC system performs. Hereafter, the possibilities for integrating the SOFC system with the ship are examined, also considering economic and environmental impact. The review shows unexplored potential to successfully integrate SOFC with thermal and electrical systems in marine vessels. Additionally, it is identified that there are still possibilities to improve marine SOFC systems, for which a holistic approach is needed for design at cell, stack, module, and system level. Nevertheless, it is expected that hybridisation is needed for a technically and economically feasible ship. Despite its high cost, SOFC systems could significantly reduce GHG, NO_X, SO_X, PM, and noise emissions in shipping.

1. Introduction

Currently, marine transport accounts for over 90% of global trade in weight [1]. Although shipping is a very efficient and cost-effective method of international transportation [2], it is also associated with much pollutant emissions [3]. Consequently, environmental regulations have been established for the marine industry.

Between 2012 and 2018, the carbon efficiency of shipping operations improved by approximately 11%. However, this progress was surpassed by a growth in activity. In the same period, carbon dioxide equivalent emissions (including carbon dioxide, methane, and nitrogen oxide) from shipping increased by 9.6% from 977 million tonnes to 1,076 million tonnes IMO [4]. European shipping contributed 19% for nitrogen oxides (NO_X), 11% for sulphur oxides (SO_X), and 8% for particulate matter (PM) to the total European emissions in 2017 [5]. Consequently, in 2018, the International Maritime Organisation (IMO) adopted an ambitious strategy to reduce the greenhouse gases (GHG) and pollutants emitted by the shipping industry. IMO is striving to reduce carbon dioxide emissions by 40% by 2030 and 70% by 2050 (compared to 2008). They also introduced Emission Control Areas (ECA) with stringent limits on NO_X, SO_X, and PM emissions [6, 7].

Four areas can be defined for emission reduction in marine applications. Firstly, the energy consumption can be reduced, for instance, with hull and propeller optimization [8, 9], routing optimization [10, 11], energy regeneration [12, 13], and grid optimization [14]. Secondly, alternative bunker fuels can be applied, for example, natural gas [15], biodiesel [16], and low-sulphur diesels [17]. CO_2 and sulphur emissions mainly depend on the fuel composition and the conversion efficiency. Methane, NO_X, and PM emissions also depend heavily on the conversion process, for instance, combustion conditions [18]. Consequently, the selection of an alternative marine fuel should be combined with fuel conversion technology. Thirdly, fuel conversion can be improved (e.g., two-stage turbocharging, heat recovery, and late miller-timing). Fourthly, exhaust gases can be treated. Scrubbers or selective catalytic reduction can be used to reduce NO_X and SO_X emissions [19]. Moreover, onboard carbon capture could offer a transitional solution to reduce carbon emissions in the short term [20]. Although remarkable improvements have been made, ship operators and shipbuilders are indicating that radical changes in the power generation system and its fuel source might be necessary to reach these future regulations and goals. Battery-powered ships are an example of such a radical innovation. Charging from the coastal power grid may achieve zero emissions during sailing, and when renewable electricity is used to charge the batteries, low life cycle emissions can be guaranteed as well. So far, batteries have been applied in ships with short mission requirements, for instance, tugs and ferries [21]. However, due to their low energy density and high cost, batteries are not considered a viable solution for large ocean-going vessels [22].

Many researchers consider fuel cells a promising solution for low-emission power generation on ships [23–27]. Fuel cells convert chemical energy directly into electrical energy, which makes it possible to reach high efficiencies. Besides high efficiency, these devices have several advantages for marine applications compared to diesel engines: low emissions, good part-load characteristics, high redundancy, low maintenance, and low noise and vibrations [24]. However, implementing fuel cells in combination with alternative fuels still struggles with high capital expenses, large fuel storage, lack of alternative fuel infrastructure, short lifetime, and slow transient behaviour [24, 28].

The low-temperature proton exchange membrane fuel cell (LT-PEMFC) is currently the most common fuel cell in transport applications due to its relatively high power density, low price, and quick response to load transients. However, fuel flexibility is its main limitation [23]. LT-PEMFC only tolerates low contamination concentrations due to its low operating temperature of 60-80°C [29]. This means it operates best on pure hydrogen, which requires expensive and voluminous storage. On top of that, hydrogen is currently very expensive. When using alternative fuels in combination with LT-PEMFC, a large, complex, and expensive fuel processing plant is necessary [24]. Consequently, interest in high-temperature fuel cells in combination with other bunker fuels has been increasing.

Solid oxide fuel cells (SOFCs) are characterized by a higher fuel impurity tolerance than LT-PEMFCs [23, 24]. High-temperature PEMFCs operating at intermediate temperatures (120-200°C) also inherit an increased impurity tolerance but, in general, it do not have internal reforming capabilities [29]. Natural gas (NG) and ammonia can be fed directly to SOFC systems [30], omitting the need for a large and costly fuel processing plant. Moreover, SOFC has demonstrated high system efficiencies of 50-65%, which can be even increased to 70% with combined gas turbine cycles [31, 32]. Currently, SOFC struggles with low power density, high investment cost, limited lifetime, and slow response to dynamic loads [23, 24]. Nevertheless, these four challenges can be mitigated. Firstly, high efficiency compensates for the low power-to-volume ratio. This results in lower fuel consumption, which leads to relatively smaller fuel tanks [33]. Moreover, SOFC's fuel flexibility makes it possible to use a fuel with a higher energy density at high efficiency, further decreasing the required ship volume compared to LT-PEMFC. Secondly, investment costs are expected to drop when production increases [34]. Thirdly, the lifetime of SOFCs, 30000 to 60000 hours [35], is sufficient to reach the typical five-year docking interval for most ship applications. Fourthly, SOFCs can be combined with batteries or internal combustion engines to ensure the dynamic capabilities of the power plant [24, 36, 37]. For these reasons, SOFCs are considered a promising power generation solution for long-haul marine applications [23–25, 38]. Nevertheless, a thorough review of SOFCs in marine applications does not exist yet.

This paper reviews the literature and research projects regarding SOFC in marine applications. We identify the technical, economical, and societal challenges of SOFC implementation. These insights support marine actors in their consideration of applying SOFC to ships.

First, general developments in SOFC systems are examined, which cover SOFC stacks, combined cycles, power plant components, and fuel possibilities. Next, previous studies on SOFCs in ships are discussed, which include marine power plant considerations, ship integration opportunities, and financial and environmental impacts. Finally, gaps in the current literature are identified in the review. This paper mainly covers system considerations and developments that are relevant for the marinisation of SOFC systems. Recent developments in cell materials, cell manufacturing, and stack assembly are outside the scope of this paper, as these are not specific to marine applications and are often reviewed.

2. SOFC Power Plants

The SOFCs provide electrical power, and many components support the fuel cells in their operation. Moreover, there are many options in system design and system integration for an SOFC power plant. This section discusses the important characteristics and developments in the main components of SOFC systems to get an understanding of the possibilities for a marine SOFC power plant. SOFC stacks, the balance of plant components, and combined cycles are discussed. Figure 1 shows the most relevant components in an SOFC power plant.

2.1. SOFC Stacks. An SOFC is a full solid-state device with a ceramic oxide ion-conducting electrolyte. SOFCs operate at high temperatures (500-1000°C), which offers several advantages. Firstly, precious metals are not required for the catalyst. These usually form a large contribution to the expenses of low-temperature fuel cells and reduce the tolerance to fuel impurities [39]. Secondly, high-temperature exhaust gas can be utilized in combined cycles for heating purposes or cooling purposes to increase efficiency [40]. Thirdly, some fuels such as methane and ammonia can be

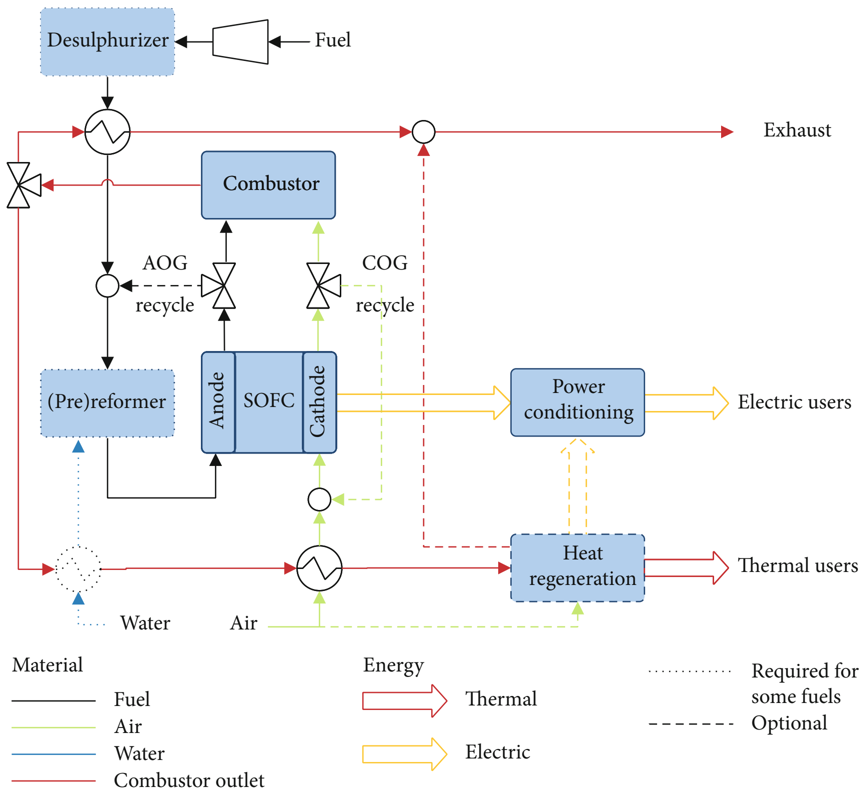

Figure 1: Schematic overview of SOFC power plants. AOG: anode off-gas; COG: cathode off-gas.

reformed internally [24]. Although the high operating temperature of SOFC brings opportunities, it also introduces large design challenges. All stack components need to be mechanically and chemically stable while being compatible in terms of thermal expansion for a large range of temperatures [41]. The fuel cell stacks often form a large contribution to the fuel cell system cost, which Battelle Memorial Institute [42] concluded to be 30% for a 250 kW NG-fuelled SOFC system.

Figure 2 shows that SOFC stack design is distinguished into planar (PSOFC) and tubular (TSOFC); the former is most often researched [44] and is dominantly used in commercial products. PSOFC has a higher power density and is easier to manufacture. Its challenges are the expensive gas-tight interconnects and the mechanical stability of the cells. TSOFC eliminates gas-tight interconnects since the fuel cell itself seals the air from the fuel and has better mechanical strength. However, the result is a lower power density and a higher manufacturing cost [45]. Welaya et al. [38] indicated the differences between PSOFC and TSOFC for marine applications by means of a thermodynamic analysis for hydrogen and LNG. Using tubular SOFC stacks resulted in higher system efficiency and thermal efficiency compared with planar stacks.

2.2. Balance of Plant Components. Components that support the fuel cells in power generation are called balance of plant (BoP) components. This includes fuel processing equipment, airflow control, thermal management systems, water management systems, and power conditioning equipment [46]. These systems contain many different components (e.g., reformers, burners, blowers, evaporators, heat exchangers, generators, sensors, and valves) and form a large part of the whole system. The components have a significant effect on system efficiency, power density, cost, and transient capabilities.

When liquid fuels are applied, the fuel is transferred to its gaseous phase with evaporators. Recuperators (i.e., counterflow heat exchangers) are often deployed to preheat fuel and air before these enter the SOFC by utilizing the thermal energy in the SOFC outlets. This reduces carbon formation and thermal gradients in the SOFC. The external air and fuel are compressed up to the operating pressure of the fuel cell before they enter the stack. Nonreacted fuel and unused air are often combined and burned in a combustor to increase the thermal energy in the exhaust stream. Diffusion or catalytic burners are often deployed since the fuel is highly diluted [47]. When anode recirculation is applied, the fuel is recycled before combustion. The gas flows in the fuel cell system are controlled with blowers, valves, and pressure regulators.

2.2.1. Desulphurisation. Most fossil fuels contain sulphur particles. For such fuels, desulphurisation must occur before any fuel reforming steps (see Figure 1) because sulphur poisons the catalysts used in reformers, shift reactors, and fuel cells [40]. The most suitable desulphurisation method depends on the fuel type and the sulphur tolerance of the fuel cell. Researchers and suppliers state that SOFCs require a sulphur content below 1 to 10 ppm, which is much more

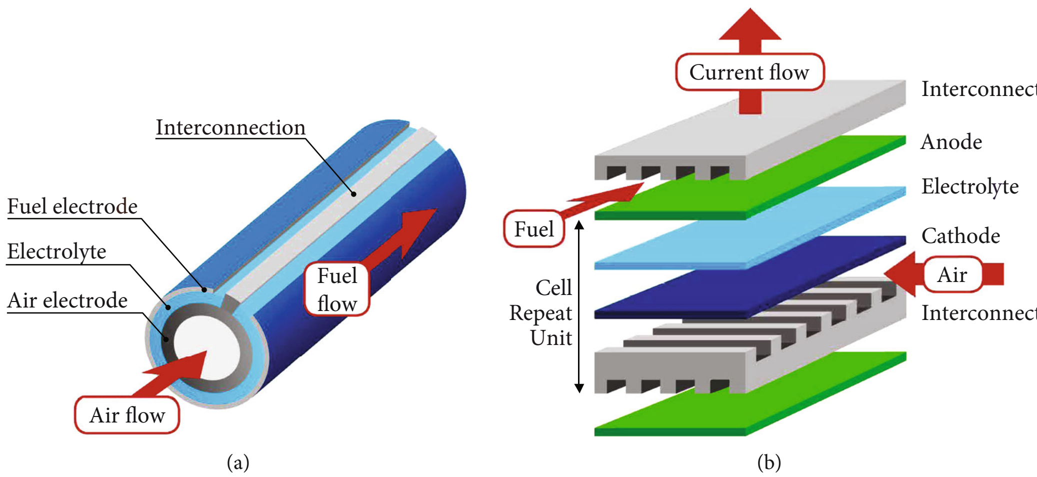

FIGURE 2: Tubular SOFC design (a) and planar SOFC design (b) [43].

tolerant than LT-PEMFC. Hydrodesulphurisation (HDS) is employed in refineries to reduce sulphur content. However, this process is not desirable for marine applications due to its size and cost [48]. Moreover, HDS is inconvenient for internally reformed SOFC (see Section 2.2.2), since a hydrogen-rich stream must be fed to the HDS reactor. Another option is to use sorbents for the selective removal of sulphur particles. van Rheinberg et al. [48] compared several commercial sorbents with experiments and proposed nickel-based selective adsorbents for fuel cell applications to reach the desired <1 ppm sulphur content. Nevertheless, the adsorbent requires regeneration and they criticized adsorbents for high sulphur fuels since the sorbent would not have sufficient capacity and the adsorption would require much time.

2.2.2. Reforming Strategy. A fuel cell converts the chemical energy that is stored in hydrogen into electrical energy. Fuel cells are fuelled with pure hydrogen or with a fuel that contains hydrogen. There are several methods to convert hydrogen carriers to a hydrogen-rich mixture, of which steam reforming is the most efficient for SOFC [49]. Steam reforming is an endothermic reaction that needs a constant supply of heat and steam.

The conversion can occur in an external reformer. Alternatively, the heat and steam produced by the electrochemical reaction in the SOFC can be used to reform the fuel internally. Internal reforming significantly decreases system capital cost and system complexity since no external reformer is needed [32]. For internal reforming, a distinction is made between direct and indirect reforming; see Figure 3. Indirect internal (IIR) reforming only makes use of the heat released from the fuel cells. With direct internal reforming (DIR), the fuel is directly fed to the anode, where the reforming occurs. DIR simplifies the system and lowers the capital cost [40]. An increased risk of carbon deposition on the anode and larger temperature gradients in the stacks (i.e., deterioration of the ceramic cell material) are challenges of direct internal reforming [32]. A prereformer is used in some studies to accelerate the electrochemical reactions in the fuel cell, improving power production [31, 50].

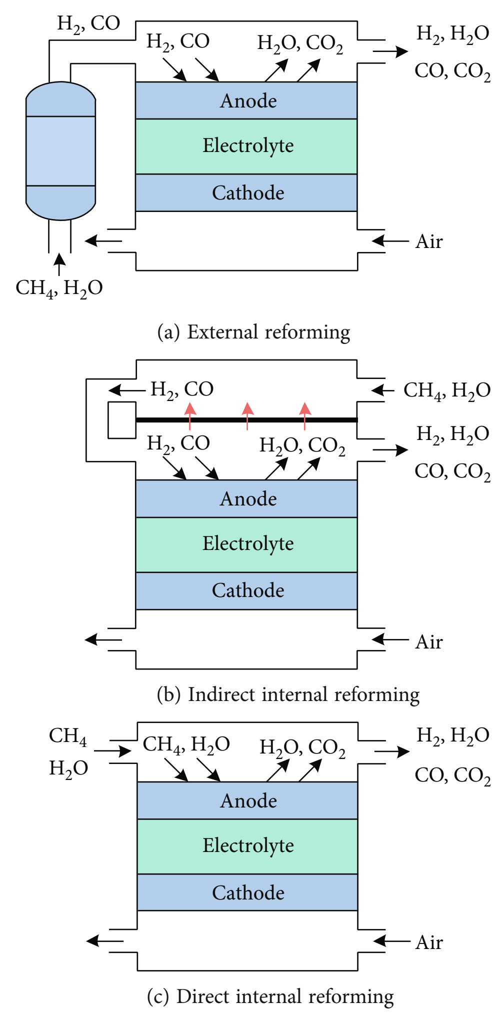

FIGURE 3: SOFC reforming types [own images based on Choudhury et al. [40]].

2.2.3. Anode Off-Gas Recirculation. Steam is often necessary for the reforming process. The steam demand can be satisfied with a heat recovery steam generator (HRSG), driven by the exhaust heat and using demineralised water

[51, 52]. However, the anode off-gas of an SOFC already contains steam since water is produced at the anode during the electrochemical reaction. The anode off-gas (AOG) can be recirculated using blowers or ejectors, mixed with new fuel, and fed back into the fuel cell. This lowers the steam generator requirements, leading to lower capital cost [53]. Recycling the fuel also leads to lower local fuel utilisation [54] and a more homogeneous temperature and particle concentration distribution through the stack [55], which are beneficial for the cell lifetime [56]. In addition, a fuel cell does not utilize all the fuel that is fed to its anode. By recycling the fuel, nonreacted fuel is utilized, slightly enhancing the overall system efficiency [57–59]. There are other advantages to anode recirculation. Firstly, less preheating of the fuel is needed. Secondly, the fuel that enters the fuel cell is already partially reformed, which reduces the stress on the reformation catalyst [60]. In the studies by Jia et al. [53] and Peters et al. [61], it was found that an SOFC system with internal reforming and anode off-gas recirculation results in a 16-20% higher system efficiency compared with an externally reformed SOFC system without AOG recirculation. However, steam-to-carbon ratio control, which is required to prevent carbon deposition, might be less accurate [50]. On top of that, the high operating temperature adds challenges to the blower or injector design in the recirculation system. Peters et al. [58] and Hollmann et al. [62] proposed to reduce the temperature of the recirculation loop to enable the use of commercial blowers, which are available at operating temperatures up to 300°C.

2.2.4. Power Conditioning. Fuel cells deliver direct current, and their voltage varies, among others with current and age. On top of that, fuel cells do not handle reverse currents and ripple currents well [63]. Consequently, power conditioning equipment is necessary for an adequate and stable power source. Power converters are used to boost and regulate voltage. Transformers are often incorporated into these converters to protect the fuel cells from substantial voltage differences. Next, DC/AC inverters (three-phase inverters for nonresidential applications) are used when AC power is required. Diodes can be used to prevent reverse current flow to the fuel cell, but they introduce additional losses [64]. Capacitors can be used to filter current ripple, but they increase the size and cost of the system [65].

2.2.5. Start-Up and Cool-Down. During start-up, the SOFC needs to heat up to its operating temperature. There are two common methods for heating the SOFC. Firstly, the heating elements of the bipolar plate can be connected to an electrical power source. Secondly, the cathode air can be preheated by an electric burner and channelled through the stack, during which the inlet pressure needs to be tuned during heat-up since the flow resistance in the stack increases with temperature. For both methods, the heating rates should be limited to the allowable thermal stress of the SOFC stack, and both require similar heating energy [66]. During a shutdown, the stacks must be gradually cooled. The SOFC stack can be cooled over its cathode with air. A smaller thermal mass of the hot components decreases the start-up and cool-down times [67]. During start-up and shutdown, no air may reach the anode to prevent oxidation. This can be ensured by using a nitrogen supply system that flushes the anode or with advanced flow control. However, a nitrogen supply adds additional piping and mixing components to the system [68].

2.3. Combined Cycles. The anode off-gas contains unused fuel and thermal energy. Even when anode recirculation is applied, not all fuel fed to the anode can be converted. To improve the electrical efficiency of the SOFC system, researchers have investigated the utilisation of this exhaust gas for combined cycles (see heat regeneration in Figure 1). A variety of systems have been proposed. Earlier studies focused on integration with gas or steam turbines [32], which leads to a significant increase in efficiency accompanied by poor performance at part load. Next, research increased on combined cycles with Stirling engines or reciprocating engines. These offer a significant increase in efficiency at better economics and part-load performance. Baldi [69] and Tan et al. [70, 71] studied an integration concept where purified anode off-gas of the SOFC is fed to the LT-PEMFC. The aim of this concept is to decrease the cost per kW, increase SOFC lifetime, and increase transient capability. The concept was positively evaluated and is recently also introduced by Hagen et al. [72] for marine applications. The combined cycles that have more often been investigated for marine applications will be discussed in the following sections.

2.3.1. SOFC-GT. SOFC-gas turbine (GT) is the most studied combined cycle plant. In this concept, the SOFC generates electrical power with high efficiency, while the anode-off gas is combusted and expanded in a gas turbine to generate additional power. Most of the analyzed SOFC-GT plants operate under pressure, which couples the operation of the SOFC and GT. This has the negative consequence that the transient behaviour of the slowest component depends on the overall system dynamics. A pressurized SOFC system also decreases system simplicity and reliability [32]. Nevertheless, pressurized operation increases the efficiency of the SOFC by increasing its cell voltage [38, 73]. Combined cycle research shows an electrical efficiency of 58% to 76% for SOFC-GT systems [31]. Kawabata et al. [74] published the testing evaluation of the first commercially available SOFC-GT system. They tested the load-following behaviour, SOFC degradation, emissions, noise, and vibrations. Safety was also evaluated for emergency shutdown events, such as internal errors, electricity blackouts, or earthquakes. Safe outdoor operation was demonstrated at 53.6% electrical efficiency (LHV), and a practical durability of 10 years was concluded. Despite the promising numbers, off-design and part-load performance have resulted in a significant efficiency drop. Many studies concluded that high efficiency can only be reached when the turbomachinery is operating at the design condition [32, 75–77]. An absolute decrease in electrical efficiency of 23% was reported by Chen et al. [78] at 50% load with simple fuel flow control. Consequently, sustaining high efficiency requires complex control strategies [79].

2.3.2. SOFC-ST. The combusted anode-off gas can also be used to drive a steam turbine (SOFC-ST). Similar to the SOFC-GT system, the steam turbine can be used to increase SOFC system efficiency [80]. van Biert et al. [31] concluded that gas turbine integration is more attractive for SOFCs operating at relatively low fuel utilisation, moderate cell voltages, and high stack temperatures. A steam turbine is the better choice for relative low stack temperatures and high voltage. They also concluded that the average stack power densities for a pressurized SOFC-GT and SOFC-ST are, respectively, 75% and 25% higher compared with a stand-alone system of similar electrical efficiency. However, it is not known how this relates to the power density of the total system. Arsalis [81] mentions that steam turbines (and gas turbines to a lesser extent) are inefficient for relatively small power plants. A significant efficiency difference was found between a 1.5 MW and a 5 MW application.

2.3.3. SOFC-RE. It is also possible to integrate an SOFC stack with a reciprocating engine (RE). These generally have better part-load, cost, and durability characteristics than gas turbines [73]. On top of that, the operation of the engine can be decoupled by bypassing the fuel directly into the engine. Rapid load transients cause degradation in the fuel cells, decreasing the SOFC lifetime. Engines can quickly respond to load changes, whereas SOFCs and turbines respond slower. Consequently, integrating SOFC and RE improves the dynamic capability of the total system and thus the lifetime of the SOFCs. All in all, SOFC-RE leads to a more cost-effective combined cycle than SOFC-GT and SOFC-ST [79].

Research by van Biert et al. [31] shows lower efficiencies for SOFC-RE than for SOFC-GT and SOFT-ST for a similar system at nominal operation. Nevertheless, they mention that this may be outweighted by the advantages of transient capability and simplicity in control strategies.

Sapra [73] investigated the optimal power split for a SOFC-RE system (RE fuelled with AOG) for three naval applications. A higher power split towards SOFC resulted in higher efficiency, but increased the total volume and weight of the total system. An optimal value was found at 28% SOFC load share, which corresponds to a combined system efficiency of 52%. This resulted in a system with twice the size, similar weight, an efficiency improvement of 9% to 11%, and a NO_2 reduction of 36% to 43%, compared with a conventional system. Sapra et al. [27] further validated the power split with engine experiments.

Wu et al. [82] investigated the dynamic behaviour of an integrated SOFC-engine system and concluded that the slow dynamics of the SOFC dominate the overall system dynamics, but they did not use a fuel bypass. They proposed to add a metal hydride reactor for H_2 addition, which improved the overall dynamic capabilities.

Although high system efficiencies were projected for SOFC-combined cycle plants in theoretical studies, most physical demonstrators have not reached the predicted efficiencies [32]. Moreover, combined cycles result in more complex plants with bigger control challenges. On the other hand, stand-alone SOFC systems have been demonstrating higher efficiency than expected [31]. Consequently, recent research has been reconsidered SOFC systems without combined cycles.

2.4. Fuel Possibilities for SOFC. Several fuel types are possible in combination with SOFCs, although several reforming and purification processes are needed for some fuels. This section discusses fuels that have been considered for SOFCs in the marine industry. While considering fuels for marine applications, attention must be paid to the associated costs and emissions in the production and distribution phases of fuels and their feedstocks. However, this comparison is outside the scope of this paper.

2.4.1. Diesel. Currently, diesel-type fuels are dominantly used in ships. They are relatively cheap and energy-dense compared to alternative fuels. In the past, heavy fuel oil (HFO), a residual from the refinery process, was mostly used in deep-sea shipping. Since 2015, its yearly usage has decreased and is partly replaced by cleaner distillates, such as marine gas oil (MGO) or blends of MGO and HFO called marine diesel oil (MDO). The sulphur content limit decreased from 3.0% for HFO to 0.1% for ultralow sulphur fuel oil (ULSFO) and MGO [83]. Because of its high energy density, common availability wide use in the marine industry, diesel has also often been investigated for SOFC systems. Fuels with low sulphur content are easier to handle for SOFC systems since it reduces the stress on the desulphuriser. SOFCs may even be able to operate stably on ULSFO without desulphurization, albeit with a small performance drop caused by sulphur poisoning [84]. However, low-sulphur fuels are more expensive since additional catalysts and chemical additives are used in the refining process [85]. Biodiesel has also been successfully used in SOFCs, externally and internally reformed [86]. However, it is expected that biodiesel will not be widely available since its production competes with food production [3, 87]. The production and distribution infrastructure, as well as regulations for diesel fuels, are in place. Due to these advantages, diesel-type fuels were often considered for SOFCs in marine applications [25, 26, 88, 89]. However, diesel is inconvenient for SOFCs since it requires a complex and large fuel processing plant [24], which lowers the power density and efficiency of the SOFC system.

2.4.2. Hydrogen. Recently, the many initiatives by companies and governments have illustrated an increasing interest in hydrogen for marine applications. The most common storage options for hydrogen are compressed or cryogenic. Cryogenic storage (at -253 C) is currently the most energy-dense option [90], making it most suitable for marine applications [24] and will be referred to as LH2 in this study. However, cryogenic storage requires insulation to keep the fuel in the liquid phase at a low temperature, and it requires cylindrical tanks to handle pressure gradients. Both increase the required ship volume for fuel storage; the volumetric energy density of LH2 storage is the lowest compared with other alternative fuels. The cooling of hydrogen to a cryogenic stage also requires much energy [90]. Liquid hydrogen is currently the most expensive alternative fuel for marine applications [33].

Although hydrogen can be used in SOFCs with satisfactory efficiency [91], 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. On top of that, internal reforming cools the SOFC stack since heat is needed for the reaction. When using hydrogen, a larger airflow is needed to cool the stack, which increases the parasitic blower power. Although it seems counterintuitive, hydrogen-fuelled SOFCs often lead to lower system efficiencies than hydrocarbon-fuelled SOFCs [92, 93]. Due to the lower power density, lower dynamic capability, and higher cost per kW of SOFCs, LT-PEMFC would be the preferred option for hydrogen.

2.4.3. Natural Gas. Natural gas's most common storage for marine applications is in cylindrical tanks at -162 C, also called liquefied natural gas (LNG). The volumetric and gravimetric energy density of stored LNG is significantly lower than that of diesel but higher than that of hydrogen. Natural gas is increasingly being used in the marine industry, meaning its fuel infrastructure and production capacity are expanding [94, 95]. 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 [96]. However, more recently, methane slip in natural gas-fuelled engines is recognized as a serious concern due to its high global warming potential [4].

Most SOFC research and commercially available SOFC systems use natural gas as the main fuel, and high efficiency has been demonstrated [32, 80, 97]. Natural gas can be directly used in an SOFC after desulphurization, but a prereformer is often applied to promote steam methane reforming to reduce the stress on the fuel cell catalyst. Opposed to an LNG-fuelled engine, methane slip is negligible [98]. Biogas-fuelled SOFC has shown comparable performance to hydrogen in terms of power production [99].

2.4.4. Methanol. Methanol can be stored in liquid form at room temperature, omitting the need for insulation and cylindrical tanks. Consequently, methanol is stored at a higher energy density than gaseous fuels. Liquid storage is even more beneficial for marine applications since irregular ship volumes can be used to store fuel. Moreover, diesel infrastructure can be used for methanol after slight adjustments [100].

Few studies examined SOFC performance fuelled with methanol [24]. In contrast with natural gas, methanol has a relatively low reforming temperature, making it convenient to reform the fuel externally [101]. Since internal reforming is usually beneficial for the cells in terms of efficiency and thermal balance, Rechberger et al. [102] added a methanator before the anode outlet to allow internal reforming of methane in the stacks. Methanol has been investigated for use directly in SOFCs [103], demonstrating high performance without notable cell degradation [104], but direct methanol SOFC systems are still in the research phase [105].

2.4.5. Dimethyl Ether. Within the last five years, dimethyl ether (DME) has received increasing attention as a fuel for the marine industry since implementation would lead to a reduction in NO_X, SO_X, and PM emissions [24, 106, 107]. Above 700 C, DME can be easily reformed to methane, carbon monoxide, and hydrogen, making it a convenient fuel for high-temperature fuel cells [108]. Murray et al. [109] concluded a high power density for SOFC systems directly fuelled with DME. One practical problem of directly supplying DME to SOFC is coke formation. This can be suppressed by adding fuel at high temperatures, but this adds extracomplexity to the system [108]. Sato et al. [110] 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.

2.4.6. Ammonia. Ammonia (NH_3) is a much-produced chemical commodity that recently received more interest in the marine industry since it can be used in modified engines and fuel cells [111]. Ammonia can be stored in its liquid form at -33 C or at a pressure of 10 bar [112, 113], and its storage is characterized by a moderate volumetric energy density compared with the other discussed fuels. Because it contains no carbon, ammonia can be used in SOFC without the risk of carbon monoxide poisoning or coke formation. Ammonia can be directly fed to the anode, where ammonia is cracked internally, which is beneficial for the heat efficiency of the SOFC system [114]. Carbon dioxide and methane are not 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 [112]. Several investigations concluded that an SOFC running directly on ammonia shows similar [114–116] or even higher [30, 117, 118] efficiency than hydrogen. Frandsen et al. [119] demonstrated with a multiphysics 3D stack model and cell experiments that internal cracking is very fast at typical operating conditions, anode recirculation appears feasible, and only negligible reforming in heat exchangers will occur. Ammonia contains no sulphur, so the desulphurization component is not necessarily for an ammonia-fuelled SOFC.

2.4.7. Fuel Comparison. Several fuel possibilities for marine SOFC systems have been presented, and a comparison is shown in Table 1. The production capacity of DME and LH2 is still very low and would require a large scale-up for marine applications. Hydrogen performs very badly in ship storage, which makes it inconvenient for long-haul applications (see Figure 4). For marine applications, the fuel cost is often a large contributor to the total cost of ownership, and current hydrogen prices are very high. Fuel cost for LNG, MeOH, and DME is similar or even less compared with MGO after compensating for the efficiency difference

Table 1: Performance of different fuels in combination with SOFC for marine applications. *Production capacity* is global [233–239]. *Energy density* includes the onboard storage system [24, 33, 73, 90, 240, 241]. *Fuel price* ranges depend on market volatility and feedstock [18, 23, 28, 179, 233, 236, 240, 242–247]. *Fuel storage price* represents the capital cost of the storage system [28, 240, 244, 246, 248–250]. *TRL* is the technological readiness level and is rated on the common scale of 1 to 9 [16, 18, 24, 96, 127, 151, 251]. The benchmark (MGO) has been compensated for the efficiency difference between diesel generators (43%) and SOFCs (55%) for comparison purposes. All data is based on LHV.

	Unit	MGO Amb. T	LH2 -253 °C	Biodiesel Amb. T	LNG -162 °C	MeOH Amb. T	DME 5 bar	NH3 10 bar
Production capacity (excl. liquefaction)	TWh/Y	600	2500	1700	38000	1000	90	1000
Production capacity (inc. liquefaction)	TWh/Y		4		5800			
Vol. energy density	kWh/m3	6000-7800	1200-2200	7200-8900	3100-3800	3300-4200	3600-3800	2300-2600
Grav. energy density	kWh/ton	6500-7400	2200-3900	7100-8600	7300-8800	3900-4500	5400-5600	2900-3600
Fuel price	€/kWh	0.03-0.19	0.04-0.54	0.08-0.13	0.02-0.18	0.04-0.12	0.01-0.07	0.06-0.16
Fuel storage price	€/kWh	0.03-0.15	1.3-9.0	0.02-0.08	0.14-1.44	0.04-0.16	0.17-0.23	0.23-0.72
Marine TRL of fuel	—	9	4	8	9	5	2	3
TRL of fuel with SOFC	—	—	6	3	8	7	4	5

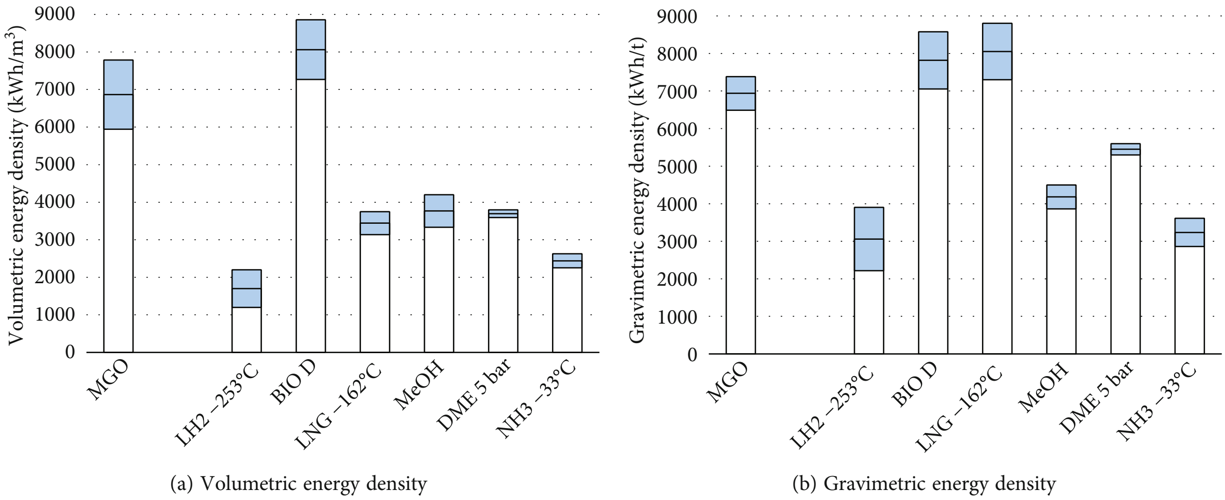

Figure 4: Energy density of future fuels including the storage system of the concerned fuel. The benchmark (MGO) has been compensated for the efficiency difference between diesel generators (43%) and SOFC (55%). Based on the LHV of fuels, the blue bars show the data ranges found in literature, projects, and supplier specifications [24, 73, 120, 121].

between diesel generators (DGs) and SOFCs. For conventional fuels, the cost of the fuel storage system is not a large economic driver. However, LH2, LNG, and DME require cylindrical or spherical tanks, which significantly increases the cost of the storage system. Especially hydrogen is very costly to store; see Table 1. Many ships are powered by diesel-type fuels or LNG, ensuring high technological readiness for marine use. Since hydrogen, methanol, and ammonia are often applied in other industries, there is much knowledge about storage, distribution, system control, and safety; however, they have not been applied at large scale in commercial vessels. Most of these fuels have also been investigated for marine engines, but research points out lubrication, cooling, ignition, knocking, and fuel slip problems [90, 122]. Moreover, the engine efficiency is often not as good as with diesel-type fuels [123, 124]. Consequently, alternative fuels could be used in combination with marine engines to reduce emissions, but the gain is larger with SOFC systems. SOFC research has focused on LNG-fuelled systems, and most commercially available systems are LNG-fuelled, resulting in high technological readiness. Most alternative fuels have been theoretically verified or simulated for SOFC cells, stacks, and systems; however, modifications to the reforming process and the system control are often necessary and not yet commercialized. When comparing the different fuels, no clear favourable candidate appears, and the choice would depend on the ship type and operational profile and should be considered in combination with the power generation system. When considering SOFC systems for long-haul ships, hydrogen seems an unfavourable option, and LNG is, in the current situation, most economically and technically feasible.

3. SOFC in Marine Applications

SOFC systems are mostly investigated for onsite power generation, for instance, in data centres and residential applications, and were initially not considered suitable for mobile applications [60]. Although an SOFC system would be too large and too complex to fit in automotive applications, its research in marine applications has increased. This means the SOFC system must comply with the operational requirements of a marine power plant, which differ much from a residential application. This section explores the requirements of a marine power plant and explores the possibilities to integrate SOFCs in marine power plants. Lastly, the practical lessons from noteworthy research projects on SOFC in marine applications will be discussed. An overview of SOFC research in marine applications is provided in Tables 2 and 3. These tables show that most marine literature considers SOFC systems using internal reforming, that methanol is not often considered as fuel for marine SOFC applications, and that recently, stand-alone cycles are more often investigated than combined cycles.

3.1. Marine Power Plants. A marine power plant must be assessed on the following criteria [24, 27]:

(i) Efficiency of marine power plant

(ii) Size and weight

(iii) Load transients and start-up time

(iv) Safety and reliability

(v) Economics

(vi) Environmental impact

An SOFC power plant performs better than conventional marine engines on some of the criteria and worse on others; the technologies are compared in Table 4.

SOFC power plants generate energy at high electrical efficiency; suppliers state 43-65% for natural gas-fuelled systems. Additionally, SOFCs maintain high efficiency at partload conditions, in contrast to diesel engines. SOFC systems generally show a broad optimum between 50% and

Table 2: Chronological overview of research in SOFC for marine applications, part one. The *SOFC power ratio* indicates the power contribution of the SOFC with respect to the total power supplied to the ship at nominal conditions.

Study type	Author	Ship type	Fuel	SOFC system	Marine power plant	SOFC power ratio	System efficiency
Challenge identification	Bourne et al. [252]	Several	Several				
Electrothermal simulation	Fang et al. [162]	Navy	Diesel		SOFC-GT	11%	S: 68%
Life cycle analysis	Strazza et al. [174]	General	Several		SOFC		
Thermodynamic analysis	Tse et al. [163]	Yacht	Methane	IR Pr.	SOFC-GT & DG	25%	S: 68%
FC comparison	Welaya et al. [130]	General	Several				
FC system design	Leites et al. [253]	Seagoing	ULSD				
Ship design	Weidle et al. [149]	Arctic	Diesel	ER	SOFC & DG	14%	
SOFC integration	Cohen et al. [150]	Naval	Diesel		SOFC+FW & DG	0-100%	
Thermodynamic analysis	Ezgi et al. [25]	Naval	Diesel	ER Amb.	SOFC+BAT	100%	S: 55%
Thermodynamic analysis	Welaya et al. [38]	General	LNG	IR Pr.	SOFC-GT		S: 66%
Thermodynamic analysis	Welaya et al. [80]	General	LNG	IR Pr.	SOFC-ST		S: 59%
Concept design	Díaz-de Baldasano et al. [88]	OSV	Methanol	ER Pr.	SOFC-GT & DG	13%	A: 47%
Review	De-Troya et al. [254]	General	Several				
Fuel cell review	van Biert et al. [24]	General	Several				
SOFC demonstrator	Nehter et al. [89]	Multipurpose	Diesel	ER Amb.	SOFC		D: 55%
Comparison	Tronstad and Langfeldt [43]	General	Several				
Technoeconomic optimization	Baldi et al. [129]	Cruise	Hydrogen & LNG		SOFC & HT-PEMFC & GT & BAT	16-29%	S: 70-73%
Thermodynamic & availability analysis	Ahn et al. [144]	Carrier	Ethane	IR Pr.	SOFC-GT & DG	30-53%	S: 61%
Energy management strategy	Rivarolo et al. [28]	Cruise	Hydrogen & LNG	IR Amb.	SOFC & DG	APU	A: 55%
Thermodynamic analysis	Evrin and Dincer [91]	Passenger	Hydrogen	Pr.	SOFC-GT & WT & SP	66%	S: 41%
Thermodynamic analysis	Huerta et al. [26, 185]	Seagoing	Diesel	ER Pr. AOG-C	SOFC	APU	S: 55%
Technoeconomic analysis	Geertsma and Krijgsman [127]	Naval	Several	ER	SOFC	100%	A: 45%
Technoeconomic optimization	Baldi et al. [23]	Cruise & carrier	LNG	IR	SOFC & DG & GG & BAT		A: 53%
Environmental-economic analysis	Kim et al. [172]	Container	Ammonia	IR	SOFC+BAT	100%	A: 59%
SOFC integration	Sapra [73]	Naval	LNG	IR AOG-RE	SOFC-RE	7-100%	A: 45-60%
Technoeconomic analysis	van Veldhuizen [33]	Cruise	Several	IR	SOFC+BAT & DG	62%, 100%	A: 60%

Table 2: Continued.

Study type	Author	Ship type	Fuel	SOFC system	Marine power plant	SOFC power ratio	System efficiency
Fuel cell review	Xing et al. [169]	General	Several				
Case study	Gianni et al. [167]	Cruise	LNG	IR	SOFC & DG	41%	A: 55%
Comparison	Dall'Armi et al. [255]	Ferry	LNG	IR	SOFC	100%	A: 55%
Feasibility study	Rivarolo et al. [137]	Passenger	LNG	IR	SOFC	100%	A: 55%
Technoeconomic analysis	Kistner et al. [173]	Cruise	LNG	ER	SOFC+BAT	100%	
Component sizing & energy management	Haseltalab et al. [139]	Dredging	LNG	IR	SOFC+BAT & DG	17-100%	S: 42-59%
Case study	Micoli et al. [152]	Cruise	LNG	IR	SOFC & DG	27.5%	A: 60%
SOFC integration	Sapra et al. [27]	General	LNG	IR AOG-RE	SOFC-RE		
Feasibility study	Micco et al. [171]	General	Ammonia	IR	SOFC+BAT	100%	

Fuel – LNG: liquefied natural gas; ULSD: ultralow sulphur diesel. SOFC system – IR/ER/PR: internally/externally/prereformed; Amb.: ambient; Pr.: pressurized; AOG: anode off-gas recycling. Power plant – DG/GG: diesel/gas generator; RE: reciprocating engine; FW: fly wheel, BAT: battery; WT: wind turbine. System efficiency – A: assumed; S: simulated; D: demonstrated. SOFC power ratio – APU: auxiliary power unit.

Table 3: Chronological overview of research in SOFC for marine applications part two. The *SOFC power ratio* indicates the power contribution of the SOFC with respect to the total power supplied to the ship at nominal conditions.

Study type	Author	Ship	Fuel type	SOFC system	Marine power plant	SOFC power ratio	System efficiency
LCA & LCCA	Perčić et al. [179]	Ferry	Hydrogen & ammonia		SOFC+BAT	100%	A: 65%
SOFC integration	Archetti et al. [138]	Passenger	HFO & LNG	ER	SOFC & DG	80%	
Spatial optimisation	Kistner et al. [146]	Cruise	LNG	IR	SOFC+BAT & DG	35%	A: 54-58%
Thermodynamic analysis	Duong et al. [164]	General	Ammonia cargo	IR	SOFC-GT	100%	S: 65%
Thermodynamic & control analysis	Wang et al. [230]	River	LNG cargo	IR	SOFC-GT	72%	S: 61%
Thermodynamic analysis	Veldhuizen et al. [207]	General	Several	PR	SOFC		S: 47-58%
System design	Hollmann et al. [186]	General	LNG & diesel	PR	SOFC		S: 47-58%

Table 4: Performance comparison between off-the-shelf SOFC systems (planar stacks, nonpressurized system and without combined cycles or batteries) and medium-speed 4-stroke marine diesel generators (derived from [23, 24, 26, 28, 42, 131, 254, 256, 257], and supplier information (Table 6)).

Criteria	Unit	SOFC	DG
Electrical efficiency	%	43%-65%	30%-45%
Vol. power density	kW/m3	2-28	30-60
Grav. power density	kW/ton	5-30	45-75
Start-up time (cold-start)	h	12-24	0.2-0.3
Start-up time (hot start)	h	0.1-0.2	0.02-0.04
Load change rate	%/min	2%-10%	10%-20%
Noise	dB (A)	40-70	80-110
Current system CAPEX (2021)	€/kW	1,500-7,000	250-400
Expected system CAPEX (2030)	€/kW	500-2,000	300-500
System lifetime	1000 h	100-150	120-200
Major maintenance interval	1000 h	30-90 (stack replacement)	40-60 (engine overhaul)

80% load [125]. This is especially interesting for many marine applications, where the maximum installed power is only occasionally used [126].

Current SOFC systems perform poorly in terms of power density (see Table 4), resulting in a large and heavy power plant. This is a big challenge for marine applications because high installed power is often required to satisfy the operational profile of a ship. Most vessels (e.g., container ships, cargo ships, and cruise ships) are volume critical, although some vessel design (e.g., high-speed crafts, naval support vessels) is driven by weight requirements [127]. Sapra [73] compared the required space and weight for a hybrid SOFC-RE system with the original diesel-electric architecture for three different ships. The SOFC-RE system was 2 to 3.7 times larger and 1.1 to 2 times heavier with a system efficiency improvement of 9% to 11% and an emission reduction of 35% to 43%.

SOFC systems are characterized by poor transient capabilities [27] because the high temperature requires the heating of a large thermal mass [24]. Their relative long startup times (12-24 hours) and slow response in operational power (2-10% load/min) form a challenge for marine applications, where significant changes in power demand are required, for instance during manoeuvring or crane operations [128]. The transient power requirements surely depend on the ship type and the operational profile, but it is certain that the transient capabilities are not sufficient for most marine applications. Complementary technologies can be used to supply additional power during peak loads [24, 36, 129, 130]. These technologies can be divided into energy storage devices (batteries, supercapacitors, and flywheels) and power generation technologies with better transient capabilities (PEMFC or diesel generators).

SOFC power plants are costly, compared with diesel generators; see Table 4. However, these prices are expected to decrease with technological advances and production scale-up. Within 10 years, the prices of SOFC systems are expected to be in the range of 500-2000 €/kW at high production capacities above 250 MW/year [42, 131]. On the other hand, the prices of diesel generators are expected to increase. Stricter emission regulations require the addition of complex aftertreatment systems, which increase the capital cost of marine diesel generator systems.

A fuel cell degrades over time, decreasing its power output [132]. Fuel cell suppliers have to tackle this by installing overcapacity, since regulations define that the life of a fuel cell is over when it is not able to deliver its rated power [60]. Although not often stated by suppliers, the electrical efficiency also decreases over the lifetime of the fuel cell stacks, incrementally increasing the fuel consumption. This is important to consider in the early stages of ship design, since it means the size of the required fuel storage increases during the lifetime of the SOFC system. SOFC suppliers demonstrated lifetimes of 30,000 to 90,000 hours at nominal load with a relative system efficiency decrease of 10 to 15% over the lifetime of the fuel cell system [35, 133]. Consequently, the stacks must be replaced regularly, which further drives up the already high price of SOFC systems. Nevertheless, operating the SOFCs at part-load conditions increases the stack lifetime, as stated by several fuel cell system suppliers. To put the SOFC lifetime into perspective, medium-speed diesel generators also need major maintenance after 40,000 to 60,000 operational hours [134, 135]. However, such an engine overhaul is not as expensive as a stack replacement.

Figure 5 compares the nominal emissions for MGO-fuelled diesel generators, LNG-fuelled engines, and LNG-fuelled SOFCs. The figure is based on the data in Appendix A Table 8. The reduction in carbon dioxide emissions from LNG engines to SOFCs is mainly attributed to efficiency gains. Methane slip does not happen in SOFC, so the CH_4 emissions are virtually zero. In total, the application of SOFC leads to a large decrease in greenhouse gas emissions. In engines, soot (C), CO, NO_X, and PM emissions originate from incomplete combustion. Since the main principle of SOFCs is not combustion (only in the afterburner), these emissions are much lower compared to diesel generators. To prevent damaging the stacks, most sulphur is extracted

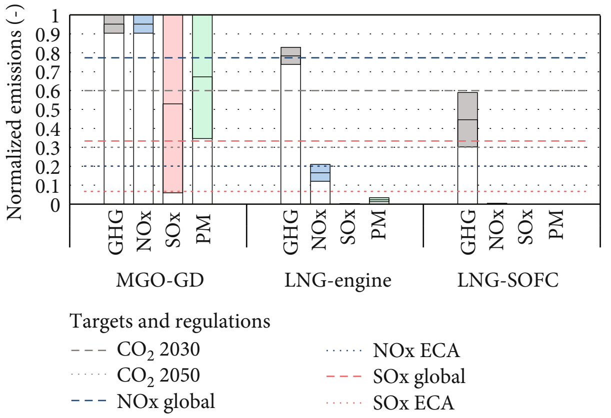

FIGURE 5: The normalized CO_2, NO_X, SO_X, and tank-to-electricity (TTE) emissions with their targets and regulations by the IMO. The colored bars indicate a range of emissions that are dependent on fuel composition and the fuel conversion processn, based on data in Table 8.

from the fuel before it enters the SOFC, so the SO_X emissions are also virtually zero. As can be derived from the figure, the application of SOFC easily satisfies all emissions regulations and meets the reduction target of 2030. The figure also shows that just LNG-fuelled SOFC systems could not reach the 70% CO_2 reduction target of 2050. Combining SOFCs with other energy-saving innovations, renewable fuels, or carbon CO_2 capture technologies would be necessary.

Besides exhaust emissions, marine power plants also produce sound emissions, propagating not only to the cabins but also to the underwater marine life. The consequences of the growing anthropogenic acoustic footprint on marine life are getting more known and are with no doubt negative [136]. Compared with engines, SOFCs strongly reduce the noise radiation from the power plant; see Table 4. Quantification of the positive impact on the aquatic environment of noise reduction by SOFCs is still necessary to evaluate how significant this advantage is.

Rivarolo et al. [137] designed an algorithm to effectively compare volume, weight, cost, CO_2 emissions, and NO_X emissions for different marine power plant and fuel storage solutions. The relevance of these criteria differed per ship application, and their case study for cruise ships showed that with the current marine regulations and SOFC prices, MGO or LNG-fuelled internal combustion engines still result in the most feasible power plant. However, it also showed, when SOFC cost can be further reduced and more stringent emission regulations will emerge, LNG-fuelled SOFC systems will become the favoured candidate.

3.2. SOFC Ship Integration

3.2.1. Hybrid Strategies. Table 4 shows that an SOFC power plant is large, heavy, expensive, and not able to quickly change its power supply. Consequently, it is expected that some degree of hybridization is necessary to reach a technically and economically feasible SOFC system [138]. The areas in which SOFC performs poorly can be partly compensated with other technologies. This leads to a wide range of hybridization strategies in which the ratio between installed fuel cell power and total installed power is an important design driver, strongly influencing the dynamic capability, capital cost, overall system efficiency (and thus fuel cost), and reduction in emissions. Evidently, hybridisation reduces the relative efficiency gains and emission improvements [139]. Tables 2 and 3 show which hybrid SOFC power plants have been investigated for marine applications. The second last column also shows that many researchers do not consider a fully SOFC power ship.

Figure 6 illustrates a generic hybrid power plant for an SOFC-powered ship. The total power plant must satisfy the following three operational boundary conditions of the ship while performing optimally on the criteria presented in Section 3.1.

(1) Maximum thermal and electrical energy demand to complete the voyage

(2) Maximum thermal and electrical power demand for propulsion and auxiliaries

(3) Transient capabilities of power supply

van Veldhuizen [33] investigated two fuel cell hybridization strategies for an expedition cruise ship using various fuels. The marine power plant consists of SOFC and diesel generators, further supported by batteries to increase transient capability. In the first strategy, the fuel cell is only used to supply power for auxiliary and hotel purposes.

This lowered the transient requirements of the fuel cell system and thus the number of required batteries. In the second strategy, the fuel cells were used for main operation (auxiliary and propulsion), and diesel generators were used as range extenders during long transits. This reduced the required size of the fuel storage tanks for the fuel cell, which is especially beneficial when using fuels that require more space in the ship to store, like hydrogen or LNG. It was concluded that the second hybrid strategy results in a smaller ship, a lower ship cost, and fewer emissions than the first hybrid strategy.

Díaz-de Baldasano et al. [88] hybridized diesel generators with methanol fed SOFC in a platform supply vessel. SOFC modules contributed 7% of the total installed power, and during normal operation, the SOFC supplied 12.5% of the total power. The SOFC modules only supply power to auxiliary consumers, due to the different voltage requirements of the thrusters. It was concluded that the plant can be implemented without limiting ship performance or operating capabilities.

Archetti et al. [138] investigated a power plant with SOFCs and combustion engines for a fixed CO_2 reduction of 20% in a passenger ship case study. To realize this reduction using LNG as fuel, it was estimated that 57% of the power should be supplied by the SOFCs. Although the analysis showed a potential solution, it was pointed out that this was not suitable for a simple retrofit, because it would load the existing engines under 40%, which is not desirable for longer periods.

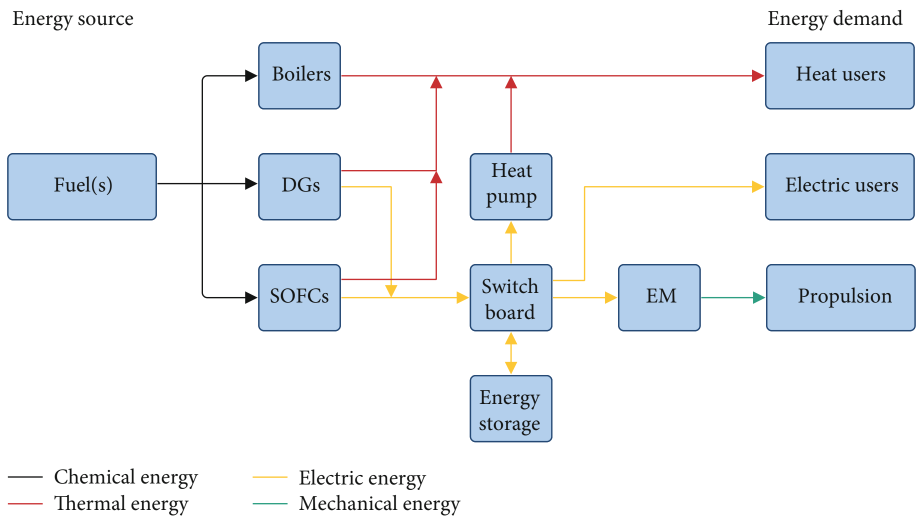

Figure 6: Generic hybrid SOFC power plant for marine applications, based on Baldi et al. [23].

Haseltalab et al. [139] researched the SOFC as a primary energy source for a dredger ship. An optimisation-based energy management approach was used to investigate the power split of LNG-fuelled SOFCs, gas engines, and batteries for a DC power plant. They showed that energy efficiency can be increased by 28% and CO_2 emissions can be reduced by 32% if the size and weight of the engine room remain unchanged compared with a conventional diesel power plant. This corresponded to a SOFC-engine power split of 17% versus 83%, respectively. A fully SOFC-powered ship resulted in a power plant size and weight increase of 70% and a CO_2 emission reduction of 53%.

Instead of separately generating power with SOFCs and diesel generators, these could also be integrated into a combined cycle by fueling the engine with anode off-gas from the SOFC (see also Section 2.3). Sapra et al. [27] performed experiments on a marine quality engine and recommended a 33-67% SOFC-ICE power split for marine applications, based on the following marine-design drivers: efficiency, space and weight, dynamic capabilities, economics, environmental impact, and noise reduction.

Evrin and Dincer [91] even explored a power plant where an LH_2-fuelled SOFC is used in combination with solar panels and wind turbines on a small passenger ship. An electrolysis plant is installed to refill the hydrogen storage when the power of solar panels and wind turbines is excessive, which leads to a ship that is powered 100% with sustainable energy. The power plant also supplies potable water to the ship. However, the proposed power plant is said to only be feasible for ships with a refuelling interval of up to 10 hours.

3.2.2. Fuel Flexibility. SOFC systems are particularly attractive for marine applications due to their fuel flexibility [23]. Currently, actors in the marine industry are not sure about the main future fuel, which is problematic since ships are built for a long lifespan. SOFC systems offer resilience and offer the option for a fuel-flexible ship, with the following two options:

(i) A ship that stores and uses two or more fuels, similar to ships with dual-fuel engines. Although this offers operational flexibility, it leads to many redundant components, since fuel bunkering, storage, and fuel handling must be present in the ship for different applied fuels

(ii) A ship design that is adaptive to two or more fuels. This can be integrated into the design by applying modular concepts at the component level [140, 141]. For an adaptive design, it is convenient to combine fuels that have similar properties in fuel storage and fuel handling, for instance, LNG and ammonia. Both fuels are gases at ambient temperature, and ammonia can be stored in LNG tanks without major design changes [142]. Another convenient option is MGO and methanol. Both fuels are stored as liquid and can be stored in irregular ship volumes such as the double bottom [143]. An adaptive design makes it possible to use a widely used fossil fuel in the short term and a cleaner alternative fuel in the future, when it becomes more widely available

Most marine research projects consider several fuels, but it is unclear which fuel is most effective for an SOFC-powered ship in terms of availability, technical feasibility, economics, and environmental impact. Moreover, a fuel-flexible ship powered by SOFCs has not been researched yet.

3.2.3. Ship Design. Fuel cells are modular, meaning the intrinsic performance of a single cell is not different from a big stack [24]. When well designed, SOFC systems have no single point of failure, as is the case with internal combustion generator sets. This results in high redundancy and thus high availability, which is an important design driver for marine applications. Ahn et al. [144] used a fault tree analysis to investigate the system availability in a large ethane carrier powered by SOFC-GT and dual fuel DG systems. A high system availability was concluded (98%) of which the turbomachinery was identified as the critical component. Availability could be further increased by increasing redundancy in turbomachinery, but this was deemed unnecessary. The modularity and low noise and vibrations of fuel cells also make it possible to spread energy production throughout the ship with minor scale losses. This decreases the grid size and decreases energy transmission losses because of shorter electricity cables [145, 146]. Decentralized power generation also makes it easier to reach high system redundancy in ships [147], because power generation can be distributed over different fire-tight compartments. This brings new opportunities to the general arrangement of the ship. Leites et al. [148] installed the SOFCs decentralized, which enhanced the safety and availability of the ship in case of damage. Weidle et al. [149] designed a concept for an Arctic patrol vessel using SOFC to generate power. The SOFCs are located near the bow to easily satisfy air intake demands and allow easy access for repair or stack replacement. The SOFCs are placed in an enclosed and isolated area to be able to shut off the room in case of hydrogen or carbon monoxide leaks. Cohen et al. [150] added that fuel cell rooms must be unmanned and separated from diesel spaces and spaces with electric equipment. They also identified ducting as an important design driver, since the air intake of SOFC is large compared to diesel generators and must be distributed to many modules. It is recommended to arrange the modules in such a way that centralized ducting is possible. Rivarolo et al. [28] studied different operating strategies for SOFC energy management on cruise ships. A distributed energy generation approach is proposed, in which the installed power of the SOFC is equally divided over the main vertical zones in the ship, meaning energy is produced close to the end-users. This offered advantages in energy efficiency and reliability but introduced challenges in control strategy, space usage, and safety requirements. In actual marine power plants, redundancy requirements often lead to oversized ICEs, especially for passenger ships, which have to comply with safe return to port regulations [151]. Kistner et al. [146] state that a decentralized fuel cell plant could minimise this oversizing and even omit the requirement of emergency power generators. They optimised the spatial layout of decentralized power generation with SOFCs on cruise ships and concluded that the economic cost of transmission losses decreased by 55% compared to a centralized configuration. Nevertheless, it is questioned whether the operational cost savings of a decentralized power system may justify the additional shipbuilding expenses of multiple machine rooms.

Micoli et al. [152] examined the possibility of an SOFC plant to supply the entire hotel load of a large cruise ship, which corresponded to 27.5% of the electrical balance. They proposed to install all fuel cells in the back of the ship, separated from the engine room, to be compliant with safe return to port regulations. An increase in the weight and volume of the power plant forced them to investigate the floating and stability capacity of the ship. They concluded that their solution meets the weight and stability requirements and could reduce CO_2 emissions by 11%. They did not include heat regeneration, which could further improve the power plant efficiency.

SOFCs produce no noise and vibrations since they contain no moving parts. Moving parts in the balance of plant components produce some, but this is much less than the noise and vibrations produced by diesel engines. This is an especially big advantage for ships that require comfort (e.g., cruise ships) or silent operation (e.g., naval ships).

3.2.4. Electric Integration. To integrate fuel cells into current marine systems, SOFC modules must be linked to the main switchboards via a transformer to adjust the voltage and possibly an inverter to convert the power to the required output [150]. Cohen noted that inverter modules can be combined for several fuel cell modules. This reduces the system's size and cost but also reduces redundancy.

Currently, most large ships use an alternate current (AC) electric grid [153], because generators provide AC power and the majority of available power electronics components are AC ([154]). However, when the majority of power is supplied by fuel cells or batteries, it can be beneficial to apply a direct current (DC) grid. Fewer transformers and switchboards are needed to supply fuel cell power to a DC grid, saving 1 to 2 % electrical loss per component [155]. Moreover, in current system architectures, many DC auxiliary loads are connected to an AC grid using converters, which are also additional power conditioning components. Consequently, employing a DC network increases the electrical system efficiency and lowers the size, weight, and cost of the system [156]. Even for a hybrid concept with major DG and minor SOFC power generation, a DC distribution could be considered. In contrast to an AC grid, synchronisation of generation units at a specific frequency (50/60 Hz) is not required for a DC grid, enabling the diesel generators to operate at their optimal speeds and reducing fuel consumption [153]. Zahedi et al. [156] estimated 15% fuel savings for offshore supply vessels with energy storage using a DC grid compared with a conventional AC system. Kanellos et al. [157] estimated space and weight savings of 30%, mainly due to smaller high-speed generators and the elimination of bulky low-frequency transformers. The implementation of DC networks on MW-scale ships is limited [158], and a new design philosophy for circuit architecture would be required to ensure reliability and safety [159]. Nevertheless, there is significant potential to increase the overall electric efficiency. The automotive industry experienced the same trend and had already demonstrated significant reductions in the size, weight, and cost of DC system components and an increase in their availability [160].

A power management system is required that successfully distributes the power of the fuel cells, energy storage devices, and any other power generators over the electrical consumers. Since SOFCs have higher efficiency and lifetime at partload, smart control in the start-up, cool-down, and power modulation of the many installed modules gives the opportunity to operate at optimal efficiency at different energy demands, although it is well known that modulation is not desirable for the lifetime of the cells. Bassam et al. [161] compared different control strategies for a hybrid fuel cell power plant in a passenger ship to reduce energy usage and thus reduce fuel consumption. It was concluded that fuel consumption can be reduced by 4% over an eight-hour voyage, compared with a classical proportional integral controller. This reduction was achieved by effectively charging the battery pack with the fuel cell by controlling the power plant with a multischeme energy management system.

In most marine SOFC studies, a standard electrical loss is assumed, and not much attention is paid to the design of the power electronics and power and energy management systems. However, a DC power supply, modularity, and high efficiency at part-load add opportunities to reduce electric losses and increase the total system efficiency.

3.2.5. Thermal Integration. SOFC makes it very appealing for cogeneration and trigeneration purposes. In marine applications, there is often a significant heating and cooling demand (e.g., heating ventilation and air conditioning (HVAC) system, hot water net, chilled water net, and steam production), which is usually met with boilers and refrigeration plants. Since these systems consume energy, the total efficiency can be significantly improved by using the exhaust gas for hot water or steam production [88]. Fang et al. [162] integrated the SOFC power plant with the thermal management system of a combatant ship. For each SOFC-GT module, a thermal port is established on the fresh water network. A total system efficiency of 67.9% was simulated. Tse et al. [163] considered different configurations of electric power, heat, and cooling generation from a methane-fuelled SOFC-GT system for the HVAC system in yachts. In the conventional configuration, the SOFC-GT system generates electricity and supplies it to the air conditioning unit and fan. In an integrated configuration, an absorption chiller cooled the air in the HVAC system. Since the cooling was not sufficient, an extradirect expansion coil was needed to condense the water to saturation. Increases in efficiency of the combined SOFC-GT and HVAC systems by 204% for a single-effect absorption chiller and 241% for a double-effect absorption chiller were reported. Duong et al. [164] use SOFCs for the propulsion of a general cargo ship and extend the system with a gas turbine, Rankine cycle, and exhaust gas boiler to provide auxiliary power for machinery and heating for crew accommodation. Their thermodynamic analysis simulates an integrated system efficiency of 64.5%. Although several methods of thermal integration have been investigated, Baldi et al. [23] identified that few SOFC studies in marine applications include, besides electrical energy demand, thermal energy demand. There seems to be a general assumption that SOFC systems can easily fulfil all the thermal demands of the ship, because the stack operates at such high temperatures. However, in an SOFC system, a large portion of the heat is already used to bring the air and fuel to the operating temperature of the fuel cell. Consequently, the outlet temperature of the SOFC system is usually in the range of 80-220 °C, dependending on the amount of heat used in the SOFC system. Ship designers should match the heat demand of the ship with the heat supply of the SOFC power plant.

3.2.6. Safety and Regulations. Although under development, clear regulations for fuel cells in marine applications are not yet available. ABS [165] published a guide for the implementation of marine fuel cell-powered systems, covering fuel storage, reforming equipment, fuel cell stacks, safety systems (e.g., venting, fire protection, and monitoring), testing, and certification. DNV GL [166] assigned a class notation to fuel cell-powered ships. This covers required documentation, ventilation, fire safety, and electrical systems. Overall, the current requirements are still generic and not specific to fuel type, fuel cell type, or ship type. Gianni et al. [167] compared the current regulations by classification societies. Although most regulations cover the same topics, some are contradictory regarding the necessity of double pipes, the categorisation of fuel cell spaces as machinery spaces, and the categorisation of fuel cell rooms as hazardous zones. Furthermore, none of the regulations state a particular fire extinguishing system for fuel cell rooms. Tronstad and Langfeldt [43] identified leakage in fuel cell modules and failure of electrical conditioning systems as the most critical scenarios. Sharifzadeh et al. [168] pointed out that safety and energy efficiency are competing objectives in SOFC system design. They found a strong trade-off between profitability and the range of the safe operating window. Taking into account the toxicity and flammability of potential SOFC fuels, gas-tight enclosures of pipelines and fuel stacks, redundant leakage detection, emergency shutdown systems, and high venting capacity are paramount in ensuring a safe system [169]. Although SOFC systems can handle minor contamination, fire smoke could disable the operation of the cells. We identified that the influence of fire smoke intake on the operation of SOFC systems has not been covered in research and regulations.

3.3. SOFC Impact. For sustainable power generation technologies, there is a clear trade-off between cost and emission reduction.

3.3.1. Economics. Earlier studies show that technologies with relatively low investment cost are generally favoured over solutions with high initial cost and long-term benefits [170]. This has two main reasons. Firstly, larger loans are harder to acquire, and more equity is required. Secondly, the future value of money is higher than the current value of money. When shifting to higher initial costs, this money is not available for other investments, resulting in higher opportunity costs. This slows down the introduction of SOFC power plants in marine applications, which are characterized by very high investment costs and savings in operational costs, although the latter is very dependent on the used fuel [33].

Geertsma and Krijgsman [127] executed a case study for the application of fuel cells in navy support ships. They proposed a methodology to review alternative power system designs based on mass, volume, capital and operational expenditure, technological readiness, fuel availability, and emissions. They concluded that for commercial use, improvements in technological readiness, efficiency, and cost of the fuel cell are necessary.

Baldi et al. [23] optimised an SOFC propulsion plant towards two competing objectives: total cost of ownership and emitted greenhouse gases. The power plant was applied to a cruise ship where it supplied a large share of the total power. A clear trade-off between cost and emissions was identified. It was concluded that LNG is the most cost-optimal fuel for SOFCs, but a significant total cost increase (33%) is required compared with a diesel-electric cruise ship power plant, as was also concluded by van Veldhuizen [33]. A 34% GHG emissions reduction was estimated, which is on top of the drastic reduction in NO_X and CO emissions. The sensitivity analysis showed that insecurities and developments in SOFC investment cost, SOFC lifetime, and fuel prices of the fuel cells have the largest influence on the economic feasibility of an SOFC-powered ship.

The additional weight or volume of an SOFC power plant practically results in a larger ship, a deterioration of the operational profile, a reduction in cargo, or a combination of those, which all have an economic cost. Micco et al. [171] estimated a 3% cargo reduction for retrofitting a commercial vessel with an ammonia-fuelled SOFC powertrain.

Kim et al. [172] extensively compared the lifetime cost of an ammonia-fuelled SOFC power plant with HFO-fuelled engines for a container ship. They concluded that an ammonia-fuelled SOFC power plant would increase the lifetime cost 5.2 times even without considering the loss of cargo but could also reduce GHG emissions by 92.1% when ammonia is produced via a sustainable pathway. For the SOFC ship, despite the high cost of the SOFC, the fuel cost remained dominant (57.8%). They concluded that when SOFCs become more cost- and space-efficient, ammonia-fuelled SOFC systems would be a good long-term solution to decrease greenhouse gases. Kistner et al. [173] did a similar comparison for an LNG-fuelled SOFC system. They included the emissions as a societal financial cost and concluded that, despite the larger capital and maintenance cost, an SOFC plant is economically viable.

For the LNG-fuelled SOFC plant, they also identified the fuel cost as the largest contributor to the lifetime cost.

3.3.2. Environment. The main purpose of SOFC implementation is emission reduction. However, only some of the considered studies actually indicate emission reduction. Exhaust gas sample measurements of a 50 kW SOFC demonstrator running on ultralow sulphur diesel (ULSD) indicate that NO_X emissions are far below the limits for ECA zones and that neither sulphur nor hydrocarbons were detected [89]. The research results of Baldi et al. [23] indicated that the absence of methane slip in the SOFC system is the strongest driver in reducing GHG emissions, compared with LNG-fuelled engines. In their study, applying an SOFC system reduced the GHG emissions twice as much as the CO_2 emissions. van Veldhuizen [33] concluded that an LNG-fuelled SOFC-powered expedition cruise ship, hybridized with diesel generators to support it during long transits, can meet the CO_2 goal of 2030 and the ECA restrictions on NO_X, SO_X, and PM emissions. This was concluded at a 20% increase in total costs over the lifetime of the ship. An ammonia-fuelled SOFC system could also reach these targets; however, the total cost of ownership increases by 69%. For a methanol-fuelled SOFC ship, the carbon dioxide emissions did not reduce sufficiently.

It is evident that the implementation of SOFC reduces ship emissions and makes it possible to comply with upcoming regulations, albeit at a very high cost. However, to judge whether SOFCs are more environmentally friendly than conventional solutions, the environmental impact over the full life cycle of the fuel as well as the fuel cell system must be taken into account. Strazza et al. [174] executed an extensive life cycle analysis (LCA) for SOFC in marine applications, considering hydrogen, LNG, and methanol. The study concluded that the environmental impact of SOFC in marine applications is dominated by the fuel production phase. From a life cycle perspective, bio-methanol and hydrogen (produced from cracking and electrolysis, respectively) are the best options to fuel SOFC in marine applications. Finally, SOFCs are recommended over conventional diesel generators, just as the life cycle study of Altmann et al. [175] concluded. Lee et al. [176] and Mehmeti et al. [177] concluded from their life cycle analyses that the manufacturing and disposal of the fuel cell contribute little to the total environmental impact (2-10%), while operating the SOFCs has a large impact (90-98%), driven by the fuel consumption. Bicer and Khalid [178] investigated the environmental impact of heat and power generation with SOFCs for hydrogen, natural gas, methanol, and ammonia. The life cycle analysis included all phases, from raw material extraction to operation (only end-of-life scenarios were not included). It was concluded that NG-fuelled SOFCs have a less negative environmental impact than hydrogen, methanol, and ammonia, because these fuels are mostly produced from natural gas, requiring additional conversion processes. However, when hydrogen or ammonia are produced from wind energy, the environmental impact was lower than with natural gas. Perčić et al. [179] did an LCA for SOFCs in ferries, considering hydrogen and ammonia, taking into account different production pathways. They considered the manufacturing phase, the well-to-pump phase, and the pump-to-wake phase and used global warming potential, acidification potential, aerosol-forming potential, and fossil depletion as environmental indicators. They concluded that SOFC-powered ferries using blue or green hydrogen or ammonia have a lower environmental impact than an equivalent diesel-powered ship. By also including the cost over its lifetime, the authors conclude that the blue ammonia-fuelled SOFC option is the most feasible option. It provides a 65%-72% reduction in GHG emissions at a cost increase of 37%-43%, where the range represents three different passenger ship case studies. Most LCAs do not consider any disposal or recycling phase, mainly because there is no information regarding the required methods. Sarner et al. [180] made the first efforts to review which recycle methods are applicable for SOFCs, but more research is needed to evaluate the environmental footprint after its lifetime.

3.4. Research Projects. Over the last 30 years, several research projects on fuel cells in marine applications have emerged. Different ship types, fuels, and fuel cell types have been investigated. At first, most research projects focused on diesel as bunkering fuel, due to the low cost, high availability, and developed infrastructure. However, problems emerged with sulphur contamination of the fuel cells and the efficiency of the whole system [24]. In the last 15 years, research projects have emerged that are focused on solid oxide fuel cells. An overview of the most noteworthy research projects on SOFC in marine applications is shown in Table 5. This section describes these projects and their practical lessons for SOFC marinisation.

3.4.1. FELICITAS. In the FELICITAS project, a methane-fuelled 250 kW SOFC system was marinised. Several power plant integration concepts were investigated, such as gas turbine trigeneration, HVAC integration, and the use of flywheels [163]. A high system efficiency (>60%) was simulated and verified with experiments, and it was noted that the SOFCs should be operated at constant load while being supported with energy storage devices. The harsh marine conditions proved to be a great challenge for SOFC implementation. SOFC power output and lifetime were adversely affected when operating under high humid and saline conditions, resulting in the research advice to develop cathode materials with higher tolerance to Cr species. An additional investigation into marine vibrations and shocks was conducted. It was concluded that the mechanical integrity of the ceramic stack can be guaranteed with off-the-shelf damped mounting and shock resistance. Furthermore, a 1 MW SOFC plant was developed for an existing yacht design. Since the necessary pipes for fuel and ventilation conflicted with bulkhead positions, it is advised to newly design SOFC-powered ships [181].

3.4.2. METHAPU. The METHAPU project focused on validating and innovating a methanol-fuelled SOFC system for cargo vessels. Another major aim was to introduce regulations regarding methanol bunkering, distribution, and storage for commercial vessels. A 20 kW prototype was marinised and tested for five months on the car carrier "Undine" while sailing. The SOFC unit, methanol tank, and fuel reforming system were placed on an open deck because this made it easier to ensure safe operation. The project was technically successful and succeeded in running the SOFC for 700 hours with methanol. From their experience, the consortium established design guidelines, an SOFC installation manual, an SOFC user manual, and a methanol bunker checklist METHAPU [182].

3.4.3. SchiBZ. SchIBZ aimed to develop a diesel-fuelled 500 kW SOFC system for oceangoing ships. The reforming process and a system concept are developed. The researchers paid extra attention to minimising the pressure drop between anode and cathode, for which they used an uncommon anode recirculation architecture. They designed a cooled recirculation loop because commercial blowers could not operate at high temperatures. A 27 kW containerised demonstrator was tested in the multipurpose vessel "MS Forester", which demonstrated an electrical efficiency of 50% on low sulphur diesel [148, 183]. In 2016, the project continued with SchIBZ2 to test the seaworthiness of the individual components, optimise them, and further develop them for operation with LNG [26, 184, 185]. The follow-up project MultiSchiBZ aims to scale up to a 300 kW system. The diesel- or LNG-fuelled system combines 12 fuel cell modules with one central fuel processing module in a 40-foot container. Low-temperature anode recirculation and a model-predictive control strategy are positively evaluated to increase the performance of the SOFC system [186].

3.4.4. GasDrive. The GasDrive consortium proposed a novel NG-fuelled power generation system, where SOFCs are integrated with an internal combustion engine. The anode off-gas of the SOFC fuels the internal combustion engine. The optimal power split between the SOFC and the engine is investigated by Sapra et al. [27]. Carbon deposition indication is researched as a diagnostic tool to define safe operating conditions and appropriate control strategies for the SOFC system. Additionally, the effect of different prereforming concepts on the electrochemistry and temperature gradients in a commercial stack was investigated. The highest system efficiency was obtained with a system using allothermal prereforming and water recirculation. They learned that both stack and system operation need to be simultaneously considered to design the most efficient SOFC system.

3.4.5. Nautilus. The Nautilus Project aims at developing, evaluating, and validating a highly efficient and dynamic integrated marine energy system fuelled by LNG for long-haul passenger ships. This energy system, responsible for catering all the heat and power needs of a vessel, consists of a SOFC-battery hybrid system and internal combustion engine- (ICE-) based generators [187]. During the SOFC system design, the target efficiency could not be reached with a simple system architecture. 40% anode off-gas recirculation is applied to increase the projected electric efficiency from 59% to 64% [188]. The consortium develops a complete design concept and digital demonstrator of a fully integrated onboard energy system for cruise ships. It was learned that combining several off-the-shelf SOFC products into a marine power plant brings many new considerations. Centralising air supply, fuel supply, reforming, exhaust streams, and power electronics could improve the power density and cost when scaling a kW plant to a MW plant, but there are technical limits to the size of these components and using combined components decreases reliability. Furthermore, extra-analysis was necessary to design the exhaust ducting because it was not known whether the backflow of exhaust gas (for instance, when one operational module is shut down) would cause issues in the SOFC modules. Additionally, a 60 kW containerised proof-of-concept demonstrator will be developed and tested to validate the design and operational strategies. A direct current busbar (400 V) is used to combine ten 6 kW SOFC modules and one 20 kW battery, because this required less power conditioning equipment, resulted in lower electric losses, and ensured scalability and modularity. This project is still in progress [189].

3.4.6. ShipFC. The ShipFC consortium is going to demonstrate the first marine ammonia-fuelled SOFC system.

Table 5: Chronological overview of research projects of maritime SOFC applications.

Project	Year	Fuel type	Fuel cell type	Ship type	Capacity of demonstrator (kW)	Reference
FELICITAS	2005-2008	LNG	SOFC-GT	Yacht	250	FELICITAS [181]
METHAPU	2006-2010	MeOH	SOFC	RoRo	20	METHAPU [182]
SchiBZ	2009-2016	Diesel & NG	SOFC	Multipurpose	100	Leites et al. [253]
GasDrive	2016-2022	LNG	SOFC-RE	Ship	-	Sapra [73]; van Biert [113]
SchiBZ 2	2017-2020	Diesel	SOFC	Multipurpose	100	Huerta et al. [26, 185]
Nautilus	2020-2024	LNG	SOFC	Cruise	60	CORDIS [189]; Ansar et al. [188]
ShipFC	2020-2025	Ammonia	SOFC	Offshore	2000	Bettini et al. [190]; ShipFC [258]
FuelSOME	2022-2026	Ammonia, MeOH, H2	SOFC	Cruise	500	Atena [259]
HELENUS	2022-2027	LNG	SOFC	Cruise	500	OpenAIRE [191]

GT: gas turbine; RE: reciprocating engine.

Instead of an afterburner, they intend to use a catalytic converter to decrease the emission of nitrogen oxides. Offshore vessel "Viking Energy" will be retrofitted with a 2 MW SOFC system, aiming at a carbon-free operation of 3000 hours annually. The biggest challenge will be scaling the 100 kW Prototech module to an ammonia-fuelled 2000 kW power plant, which is aimed to be installed in 2023. Additionally, the consortium aims to develop certification schemes for the use of green ammonia to prevent carbon emissions in the supply chain [190]. From the first lab experiment, it was concluded that a high operational temperature should be chosen to promote ammonia cracking and thus prevent ammonia slip.

3.4.7. FuelSOME. Building on the insecurity of the future fuel mix, the project FuelSOME steps into the demand for fuel-flexible power plants and aims at the development and demonstration of a multifuel SOFC system. The system will be designed to operate with ammonia, methanol, hydrogen, and mixtures of those. Their focus is on long-distance shipping. This project still has to start.

3.4.8. HELENUS. HELENUS is a recently accepted European Union Horizon research project. It strives to enable full integration of SOFCs in ship design using co-generation and combined cycle solutions for increased efficiency with multiple fuels. A 500 kW fully integrated SOFC will be demonstrated on an ocean cruise vessel. The project also aims to improve fuel flexibility by demonstrating operation with renewable maritime fuels (e.g., ammonia, methanol, Fischer-Tropsch diesel, or hydrogen). A technological and regulatory roadmap will be created to scale up the SOFC capacity to 20 MW [191].

3.4.9. Lessons Learned. LNG is dominantly researched in demonstrator projects, since it is the most used fuel in available systems, but methanol and diesel have also been successfully demonstrated. Recent projects such as Nautilus and HELENUS also include many alternative fuels in their theoretical evaluation and the attention for ammonia-fuelled SOFC demonstrators is increasing.

SOFC demonstration experiments showed that the heat losses in the SOFC system are very relevant. Heat losses in different system components are often inaccurately taken into account in theoretical analysis, which causes deviations between theoretical and demonstrated efficiency. This topic requires more attention in future research.

Although several projects demonstrated a marine SOFC system and contributed to identifying the practical challenges of marinising SOFC systems, no large-scale SOFC system has been physically integrated with shipboard systems yet. The biggest challenges for SOFCs to achieve this are reaching higher power density, lower capital cost, and manufacturing capacity. It is also not known how the power density and cost scale when going from a kW-scale plant to a MW-scale plant. However, there is an increase in the rated power of demonstrators and the degree of ship integration for current and planned projects.

4. Addressing Marine Challenges

This section provides an overview of possible developments in marine SOFC power plants that can address its main challenges, which are operation in marine conditions, low power density, limited lifetime, low transient capability, and high capital cost. The purpose is to indicate the prospects of SOFCs for marine applications from the technical and economic perspective. This section discusses possible improvements separated on cell level, stack level, module level, and marine power plant level. To relate possible improvements to the current status, an overview of all commercially available SOFC systems is provided in Table 6. Most are fuelled with natural gas and have a relatively small rated power. Figure 7 shows which manufacturers perform best on volumetric power density and electric system efficiency, which are considered important parameters for ship applications.

4.1. SOFC Operation. Thus far, SOFC systems have mainly been applied in stationary applications, such as residences and centralized power generation. In contrast to these applications, the power plant of a ship is exposed to sea wave-induced inclinations and accelerations. These could lead to lower accuracy of level sensors by sloshing of liquids, pressure variations in gas streams, increased mechanical stress in stacks and structural components, and failure of rotor pumps and compressors. Moreover, the propeller and internal combustion engines produce vibrations, which travel through the ship structures. It has not been extensively researched whether current SOFC systems can be safely operated when exposed to these conditions and how these conditions influence the operation and durability.

Moreover, the saline and humid air conditions introduce challenges for SOFCs. The influence of air humidity on the performance and durability of state-of-the-art cathodes (LSM and LSCF) has been researched by Liu et al. [192]. The cathodes were stable when feeding air with typical water vapor concentrations (3 vol%) and even concluded to be better than using dry air, because the surface exchange reaction rate increased. However, cell degradation greatly increased for higher water vapor concentrations (5-20 vol%). In a 1500 h durability test, Hagen et al. [193] showed that humid air (4 vol%) makes LSM cathodes perform worse and less durable when the polarisation is sufficiently large. For seas and oceans, humidity of 0.5% to 3% is common, imposing no large performance or durability reductions on the SOFC. However, humidity in the air stream will accelerate corrosion from Cr and Si to the cathode. For this reason, Yang et al. [194] recommend to supply the cathode with dry air. Liu et al. [195] investigated the influence of salt content in the air feed for the same cathode materials. At 30 mg/L NaCl, the increase in cell degradation was negligible for LSM cathodes, while LSCF cathodes showed decomposition of the cathode material. Thambiraj et al. [196] performed single-cell experiments with 1.6 and 250 mg/L NaCl content in the cathode air. 1.6 mg/L salt content during 850 operational hours leads to a 200 mV drop because of delamination, whereas clean air only leads to a voltage drop of 25 mV in 660 hours. They conclude that air filters are

Table 6: Overview of relevant commercial SOFC systems that are currently or almost available. The proven lifetime is not the lifetime that the supplier expects but what they actually demonstrated.

Supplier	Model	Fuel	Rated power kW	Electrical efficiency	Total efficiency	Power density kW/m3	Power density kW/ton	Proven lifetime h	Source
Adaptive Energy (NA)	Endurance	LPG	1	20%	—	7.0	36.8	15000	Adaptive Energy [260]
Aisin Seiki (Asia)	Ene Farm	NG	0.7	47%	90%	3.7	7.3	—	Mcphail et al. [261]
AVL (EU)	SOFC CHP	HC	10	60%	95%	—	—	>80000	Moradi [262]
AtrexEnergy (NA)	-	JP-8	1.5	40%	—	3.2	9.2	>10000	Mcphail et al. [261]
Bosch (EU)	FC505	NG/H2	10	60%	85%	—	—	—	BOSCH [263]
Bloom energy (NA)	Energy server 5	NG	300	53%	—	10.6	19.0	5000	Bloom Energy [264]
CEA (EU)	—	NG	15	55%	—	—	—	>8000	EFCF2020
Convion (EU)	C60	NG	60	60%	83%	4.4	-	>13700	Convion [265]
Delphi (NA)	B-level	HC	2	30%	—	—	—	>10000	Blake [266]
Doosan (Asia)	CHP	NG	10	54%	90%	16.8	—	-	Leah et al. [267]
Doosan (Asia)	PureCell 400	NG	440	43%	90%	7.1	—	—	Doosan [268]
Fuel Cell Energy (NA)	SureSource4000	NG	3700	60%	—	2.0	—	—	Fuel Cell Energy [269]
Fuji Electric (Asia)	-	NG	50	50%	80%	1.6	—	>3000	EFCF2020
h2e POWER (Asia)	Leonardo	NG	1.3	40%	95%	2.6	—	>40000	EFCF2022
	Galileo 1000N	NG	1	40%	95%	17.0	4.8	>40000	h2e POWER [270]
Hitachi Zosen (Asia)	—	NG	20	52%	—	—	—	>4000	EFCF2020
—Huaqing Energy (Asia)	—	NG	25	47%	-	—	—	—	EFCF2020
Kyocera (Asia)	—	NG	3	52%	90%	2.3	8.0	>89000	Suzuki et al. [133]
Mitsubishi (Asia)	MEGAMIE	HC	210	55%	73%	2.0	7.6	>4100	Power Mitsubishi [271]
Miura (Asia)	FC-5B	NG	4.2	50%	90%	—	—	—	Miura [272]
Osaka gas (Asia)	192-AS1	NG	0.7	55%	87%	27.8	8.2	-	Osaka Gas Co [273]
Solidpower (EU)	BG-60	NG	5.2	60%	90%	3.5	9.2	>40000	Hexis AG [274]
Tokyo gas (Asia)	—	NG	5	65%	—	1.4	—	—	EFCF2020
Upstart Power (NA)	Upgen NXG	LPG/NG	1.25	-	-	16.0	30.6	-	Power [275]
Watt (NA)	Imperium	LPG/NG	0.50	20%	—	8.7	24.0	—	WATT [276]

Fuel: H2: hydrogen; HC: several hydrocarbons; JP-8: jet fuel; LPG: liquefied propane gas; NG: natural gas.

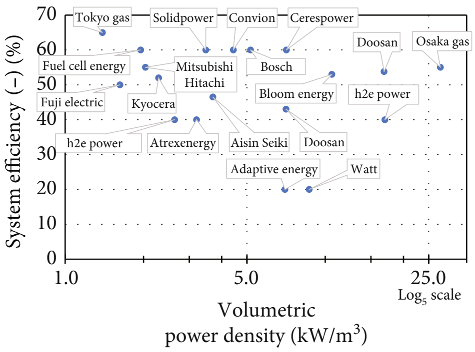

FIGURE 7: Rated efficiency and volumetric power density of commercially available SOFC systems.

needed to avoid NaCL reaching the cathodes. Besides effects on the fuel cell itself, salinity also corrodes other parts in the SOFC system, such as metal cell interconnects or compressors [197]. Luckily, air desalinisation is not new for marine applications, since it has been used for many years for marine gas turbines [198].

The long start-up and cool-down times of the SOFCs introduce challenges for practical operation. In applications where much unanticipated power is needed, a backup system should deliver the required power when the SOFC is still heating up. From this perspective, it would be favourable to use SOFC systems in applications with very constant operational profiles that are known in advance. The design rationale of the operational requirements for marine power plants might be reconsidered when applying SOFC power plants. A defined amount of power might be continuously delivered by SOFCs to reduce start-up and cool-down times in order to limit cell degradation. Many ships always require some power for auxiliary functions, even when berthed. In port, this could offer low-emission energy usage, where currently high-investment shore power infrastructure is needed. When the energy demand of the auxiliaries is low, the excess power can be used to charge the support batteries or even delivered to the electricity net.

4.2. Power Density. Power density can be improved at each level of an SOFC system, for example, starting from the improvement of the active layers in a single cell up to reducing the size of or omitting specific BoP components. Moreover, not all system weights and volumes scale proportionally to the rated power; hence, a scaling effect may be expected: large SOFC systems may achieve higher power densities than smaller systems employing the same technology [199].

The power density achieved at cell level is determined primarily by the electrolyte and electrode materials selected, their conductivity and thicknesses, active electrode and catalyst area, operating temperature, and pressure [200]. While the majority of commercially available systems rely on robust, thick electrolyte supported cell types, designs with thin electrolytes-supported on anode or metal substrates feature potential power density improvements. The potential power density improvements may be significant. For example, metal-supported designs achieve 2.8 A/cm^2 at 0.7 V and 650°C [201] which is a factor 10 higher than the first generation based on the same concept. However, structural integrity remains a challenge for anode-supported designs, as is the use of metals at high operating temperature [202].

Flat-tubular SOFCs have the tubular stack advantages of easy gas-tight sealing, thermal robustness, and ease of fabrication while also profiting from planar advantages such as low ohmic resistance and high power density. The fuel flows through anode-supported, extruded channels. Parameters such as the number of air channels, wall thickness, width, and height of these air channels can be varied to optimise cell performance and mechanical strength. A review of Khan et al. [203] showed that the performance of these cells increased three to four times since their introduction in Kim et al. [204] by using different materials and architectures. Ilbas et al. [205] proved a 20% increase in power density compared with tubular stacks using a 3D cell model. Although this cell build is still in the research phase, its developments are also being put into practice by Kyocera, Japan, and KIER, South Korea [203].

Large power density improvements may be achieved through stack design as well. The Compact Solid Oxide Architecture (CSA) stack by Fuel Cell Energy, for example, is reported to achieve up to six times the power to weight and eight times the power to volume compared with previous stack design, achieving 467 kW/ton and 778 kW/m^3 at only 0.29 A/cm^2 [206]. Although the power density of even today's stack technology is sufficiently high for most applications, the relatively large BoP of SOFC systems paints a very different picture. In fact, the BoP can easily make up as much as 90% of the total system mass and volume. For example, a 200 kW proof of concept built by Fuelcell Energy is reported to fit in a 20-foot container, thus achieving a power density of about a factor 10 lower than the power density reported at stack level [206]. Nevertheless, power density has not been as large of a design driver for most commercial SOFC systems as it would be for marine applications. It would be beneficial to tailor the design process to the marine requirements, rather than adapt existing designs with different initial requirements to the marine conditions.

For large-scale marine power plants, the desulphurisers, filtering equipment, blowers, and control architectures could be centralized for a multitude of SOFC modules, which would positively influence the power density and specific cost of the system with a slight reduction in system reliability. Moreover, air ducting is expected to require much ship volume. The specific air flows required for SOFCs are four to six times higher than those of diesel engines, because of the high air excess ratio that is required to cool the stack internally. Cathode air recirculation may reduce overall oxygen utilisation and thus limit the primary airflow and, consequently, the size of air ducting channels [49]. Cathode air recirculation could also increase the heat recovery capacity due to a higher flue gas temperature [207]. A more novel concept to reduce air intake uses SOFC stacks with liquid cooling, which has the additional advantage of a smaller parasitic power consumption. This was researched by Promsen et al. [208] for tubular and planar cells, who concluded that liquid cooling improved the temperature distribution inside the stack, improving the electrochemical performance. Nevertheless, this requires a completely new stack and system design, new operating principles, and a coolant suitable for high-temperature operation.

While sometimes overlooked, it is indispensable to consider the entire system when designing a compact and lightweight SOFC system. This calls for a holistic design approach, since choices at the system level affect stack and cell performance, and vice versa. For example, the removal of a preheater or prereformer may reduce the size of the BoP but reduce both the power density and the lifetime achieved by the stack [209].

4.3. Lifetime. Lifetime is an important aspect of maritime power generation, as the number of annual operational hours is typically high on many ship types. In contrast to the low-temperature fuel cell types, SOFCs are primarily considered for stationary applications and uninterrupted power supply, for example, data centres [210]. As these applications require the system to deliver for many hours per annum, lifetime and reliability have been major aspects of product development. First of all, high temperatures increase sintering speeds, creep, and crack growth, which alter the microstructural morphology of the cells and affect their electrochemical performance. In addition, high operating temperatures affect the chemical stability of the materials, including the electrolyte, the electrodes, and especially the interconnect. Therefore, material selection and microstructural design play a key role in reducing degradation at the cell level [211]. The development of new materials for SOFCs is continuously evolving, for example, bilayer electrolytes and new electrode morphologies [212].

Secondly, large internal temperature gradients are established over the stack to avoid a large airflows for cooling. These temperature gradients may be even higher locally, due to the differences in the magnitude of the exothermic electrochemical reaction. The presence of internal endothermic fuel reforming or cracking reactions may worsen the situation even further [213]. Temperature gradients result in thermal stress and potential delamination of the individual layers in the cells. Matching of thermal expansion coefficients helps to mitigate this issue, for which interlayers and composite electrodes may be applied [214]. In addition, researchers have proposed to adjust the catalyst loading spatially to control internal fuel conversion rates [215].

Carbon deposition may be encountered in case hydrocarbon fuels are used due to unwanted side reactions on the anode catalyst. Although carbon deposition may be suppressed through the supply of excess reforming agents, this generally negatively impacts cell life and efficiency. Alternatives for the nickel catalysts that have a low selectivity for solid carbon formation may be used instead, such as ceria-based anodes [216]. Both fossil fuels and biofuels typically contain small quantities of contaminants that may poison or react with SOFC electrodes, such as sulphur, chlorine, and potassium [217]. In addition, poisonous substances may migrate or evaporate from other parts of the system.

Chromium evaporation is commonly encountered in high-temperature alloys, which leads to irreversible performance loss at the cathode [218]. This issue can be addressed by applying surface coatings or modifications to the used alloys [219]. Ammonia, seen as a potential future fuel in the marine industry [220], does not contain carbon or these other contaminants. However, recent stack experiments showed that ammonia causes nitridation of the separator steel and the nickel catalyst. Although initial nitridation did not negatively influence cell performance, long-term nitridation deforms the stack components and causes local alternations or even blockage of the fuel channels [114]. Methods should be investigated to reduce or prevent nitridation.

It is generally acknowledged that dynamic operation influences the lifetime of SOFCs negatively [69, 221]. Effectively controlling SOFCs and other power generation components can stabilize the operation of the fuel cells, reducing cell degradation [169]. Parhizkar and Hafeznezami [222] optimised the operation of SOFC systems, taking into account several degradation mechanisms and simulated a 7.4% increase in system productivity. Lai et al. [223] compared a standalone dynamically operated SOFC plant with a steady-state-operated SOFC supported by combined cycles delivering power to the transient loads. They concluded that steady-state operation of the SOFCs is beneficial for the levelized cost of energy because of the reduced number of stack replacements. Marzooghi and Raoofat [224] proposed using a fuzzy-PI controller to reduce SOFC degradation of dynamically operated SOFC systems, which turned out to be a satisfactory control strategy. Although research in the control of SOFC systems to increase lifetime has been increasing, very few degradation experiments have been performed at the system level [225]. Moreover, most degradation experiments were executed in steady-state on nominal conditions. For marine implementation, it would be beneficial to investigate the differences in lifetime when the stacks are operated at part-load or with transient loads.

Improving lifetime remains an important aspect of SOFC development. There is a large number of mechanisms affecting degradation at the cell, stack, and system level. Consequently, the lifetime can be improved through a large variety of developments, but often there is a trade-off versus system efficiency and power density. The lifetime of existing SOFC products is already sufficient for replacement intervals that are comparable to major overhauls of marine internal combustion engines, but further improvement of SOFC durability will be beneficial for commercialisation.

4.4. Transient Capabilities. SOFC systems that are designed for stationary applications are optimised for load profiles with small and few load changes. However, most marine applications require quicker load changes. The transient response of electrochemical cells is inherently fast due to the small timescales of the electrochemical reactions. Still, the transient response times of SOFC systems are notoriously long, for which the large thermal mass of the system and the response times of BoP components are often identified as the culprits [226]. While these explain the long times

Table 7: Overview of identified research gaps or research directions in marine SOFC research.

Target	Research gap or direction	Level
Increase power density	Metal-supported SOFCs	Cell
	Flat-tubular SOFCs	Stack
	Liquid cooling of SOFCs	Stack
	Centralising balance of plant components	System & ship
	Hybridisation with diesel generators	Ship
Increase lifetime	Spatial catalyst loading to control fuel conversion and thermal gradients	Cell
	Quantification of lifetime enhancement at part-load operation	Cell & stack
	Long-term degradation behaviour for transient operation	Cell & stack
	Energy management system optimised towards SOFC lifetime	System
Increase transient capabilities	Low-temperature operation	Cell
	Improved flow field design	Stack
	Advanced thermal management and control	System
	PEMFCs fuelled with anode off-gas of SOFC	System
	Hybridisation with batteries	Ship
Decrease capital cost	Development of new materials and manufacturing methods	Cell & stack
	Decrease cost of control architecture and power electronics	System
Efficient operation	Anode off-gas recirculation to increase electric efficiency	System
	Cathode off-gas recirculation to increase heat efficiency	System
	Smart control to operate at optimal efficiency for different energy demands	System & ship
	Efficient waste heat recovery for ship consumers	Ship
	Direct current architectures	Ship
	Decentralized power generation	Ship
Safe operation	Effect of fire smoke on SOFC operation	Cell & stack
	Effect of salinity and humidity on SOFC operation	Cell & stack
	Effect of inclinations and accelerations on SOFC technology	System
	Effect of propeller or equipment vibrations on SOFC technology	System
	Marine fuel cell regulations specific for SOFCs	Ship
Low environmental impact	Operation of SOFC system with renewable fuels	All
	Disposal and recycling methods of SOFCs	Cell & stack
	Environmental impact of reduction in sound emissions	Ship

Table 8: Tank-to-electricity (TTE) emission comparison between off-the-shelf SOFC systems and medium-speed 4-stroke marine diesel generators fuelled with MGO (1.5% S) or LNG. Derived from [23, 123, 174, 175, 277–280], and supplier information.

TTW emission		Targets and regulations		Emissions per system		
		2030 target	2050 target	DG (MGO)	DG (LNG)	SOFC (LNG)
CO2	g/kWhe	60%	30%	600-660	500-530	350-450
CH4	g/kWhe	—	—	0	2-4	0
CO2-eq	g/kWhe	—	50%	600-660	530-550	350-450
		Non-ECA 2020	ECA 2020	DG (MGO) 0.1-1.5% S	DG (LNG)	SOFC (LNG)
NOx	g/kWhe	<7.7	<1.96	9.5-12	1.2-2	0.025-0.045
SOx	g/kWhe	<2 (0.5 %m/m)	<0.4 (0.1 %m/m)	0.4-6	0.008-0.016	0
PM	g/kWhe	<2 (0.5 %m/m)	<0.4 (0.1 %m/m)	1.6	0.007-0.0018	0

required for a cold start, neither provides a satisfactory explanation for the slow response once the system has reached its operating temperature.

Transient limitations in a hot and operating system originate primarily from thermal management challenges. SOFCs are usually cooled by cathode air, thus avoiding the need for high-temperature coolants. Although this simplifies the system, it leads to large airflows and thermal gradients due to the limited heat capacity of air [227]. The actual amount of cooling needs to be carefully controlled during transients to prevent local subcooling, overheating, or thermal stresses. However, the combination of solid materials with a high thermal mass and gaseous coolant with a low thermal mass causes long stabilisation times. Consequently, the point of operation needs to be changed slowly to give the airflow controller time to respond to the delayed change in the air outlet temperature [228].

The transient response may be improved by increasing the safety margin against thermal overloading, for example, by operating the SOFC well below the maximum temperature and maximum temperature gradient. However, both compromise the power density and efficiency as the stack resistance or air stoichiometry are increased. Alternatively, the transient response may be improved through algorithms that control the airflow proactively, for instance, using model predictive control [229]. Wang et al. [230] managed to increase thermal response time by 50% by using a fuzzy PID controller for power regulation and a feedforward controller for the thermal regulation. Hollmann et al. [186] used a controller that considers electrochemical and transport characteristics to predict the system behaviour over several minutes. The controller successfully increased the transient capability during testing on the operational profile of a cruise and cargo ship.

4.5. Capital Cost. While fuel costs will be reduced by SOFC-based power generation, these savings are still not sufficient to justify the high capital cost. The current price of SOFC power plants may vary from 1500 up to as much as 22,000 e/kW depending on the system configuration and size. Although this is at least one order of magnitude higher than heavy-duty diesel generator sets, the cost may be substantially reduced by advanced manufacturing and scale up. A detailed cost analysis by Scataglini et al. [131] reveals that the expected system cost of SOFC combined heat and power generation products may be reduced from 13000 e/kW for an annual production volume of 100 units of 1 kWe to 500 e/kW for 50,000 units of 250 kWe. However, the challenge lies in attaining such production volumes at the current price level.

The capital cost of SOFCs may be further reduced through the adoption of more affordable materials or by increasing the power density and, thus, reducing the cost of materials (see Section 4.2). Harboe et al. [34] identified that optimising the structural design of SOFC stacks to obtain a minimum contact resistance between the stack contacting areas is a key element in achieving cost-efficient stack design by reducing material usage. Various research groups are, for example, working on reducing the operating temperature of SOFCs, as this would allow the introduction of cheaper materials, easier assembling methods, and the use of off-the-shelf components [231]. The latter is particularly important as the balance of plant can make up a large part of the total system size, weight, and cost, while the low production volume of SOFCs today makes the development of dedicated BoP components particularly expensive, for instance, high-temperature anode recirculation blowers. Cost analyses point out that the stack manufacturing, control architecture, and power conditioning equipment contribute the most to the cost of SOFC systems [42, 232], so cost reduction should initially be aimed at these components.

5. Conclusion and Future Outlook

This paper reviews solid oxide fuel cells (SOFCs) for marine applications. These electrochemical devices could be used to reduce NO_X, SO_X, PM, and GHG emissions. Developments in SOFC power plants and fuel possibilities are discussed, followed by the research efforts regarding ship integration, which cover hybrid strategies, fuel flexibility, spatial layout, thermal and electric connection, operating strategies, and safety. Compared to land-based systems, the marinisation of SOFC systems introduces new challenges in design and integration. The SOFC systems must be able to withstand accelerations and inclinations which most commercial systems are not designed for. Moreover, air salinity and humidity can potentially deteriorate power production and increase degradation. On top of that, ships often require higher load transients. Thus, SOFCs should be combined with energy storage devices or components with higher transient capabilities.

Implementing SOFC in ships is currently difficult because of its low power density, short lifetime, slow transient behaviour, and high capital cost. However, these disadvantages could be outweighed by the high efficiency of SOFCs and the reduced emissions, which would be even more favourable in case an emission tax is introduced. Nevertheless, it is expected that hybridisation with internal combustion engines and batteries is needed to design a marine power plant with feasible size, cost, and transient capabilities.

On the SOFC system level, several developments are indicated that can potentially address the challenges of marine implementation, such as cathode off-gas recirculation, model predictive control, and liquid cooling. When considering whole marine power plants, DC grid architectures, centralized BoP components, and decentralized power generation can offer improvements.

We suggest the matching of heat supply and demand, the matching of transient capabilities and the operational profile of the ship, hybridisation strategies, and the effects of marine conditions on SOFC operation as important topics for further research. A full overview of the identified research directions is shown in Table 7.

LNG-fuelled SOFCs allow ship owners to meet the IMO regulations for NO_X and SO_X emissions and the 2030 CO_2 target, when SOFCs deliver the majority of shipboard energy. To reach the IMO $_{CO2}$ target of 2050 using SOFC systems, renewable fuels and other energy-saving technologies would be necessary. Carbon-free ship operation should not be the main goal; converting renewable fuels with high efficiency over the whole life cycle should gain the focus. Although implementing SOFC in ships still faces technical, economic, and design challenges, it is a promising solution for the marine industry to decrease NO_X, SO_X, and PM emissions while benefiting from noise reduction and increased reliability.

Appendix

Data for Emissions Graph

The data used to generate Figure 5 is shown in Table 8. For this data, SOFC systems fuelled with LNG and without combined cycles are used since these are mainly commercially available. The emissions of DG are without after treatment. The presented emissions are just tank-to-propeller emissions and are calculated with 55% SOFC efficiency and 43% DG efficiency.

Nomenclature

AOG: Anode off-gas
APU: Auxiliary power unit
BAT: Battery
BoP: Balance of plant
COG: Cathode off-gas
DME: Dimethyl ether
ECA: Emission control area
ER: External reforming
GHG: Greenhouse gases
GT: Gas turbine
HDS: Hydrodesulphurisation
HRSG: Heat recovery steam generator
HT: High temperature
HVAC: Heating, ventilation, and air conditioning
ICE: Internal combustion engine
IR: Internal reforming
LCA: Life cycle analysis
LH2: Liquefied hydrogen
LHV: Lower heating value
LNG: Liquefied natural gas
LT: Low temperature
MeOH: Methanol
MGO: Marine gas oil
PEMFC: Proton exchange membrane fuel cell
PM: Particulate matter
RE: Reciprocating engine
SOFC: Solid oxide fuel cell
ST: Steam turbine
TRL: Technological readiness level.

Data Availability

The authors confirm that the data supporting the findings of this study are available within the article. Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors' Contributions

B.N. van Veldhuizen did the conceptualisation, analysis, and writing of the original draft. L. van Biert worked on the conceptualisation, writing the original draft, review, and editing. P.V. Aravind was assigned for conceptualisation and supervision. K. Visser did the writing—review, editing, and supervision.

Acknowledgments

The research is supported by the European Consortium "Nautilus". The Nautilus Project (grant number 861647) aims at developing, evaluating, and validating a highly efficient and dynamic integrated SOFC fuelled by LNG for long-haul passenger ships.

References

[1] T. R. Walker, O. Adebambo, M. C. Del Aguila Feijoo et al., "Environmental effects of marine transportation," in *World Seas: An Environmental Evaluation Volume III: Ecological Issues and Environmental Impacts*, Elsevier, 2018.

[2] IMO, *Introduction to IMO*, 2020, https://www.imo.org/en/About/Pages/Default.aspx.

[3] K. Andersson, S. Brynolf, J. F. Lindgren, and M. Wilewska-Bien, *Shipping and the Environment, Improving Environmental Performance in Marine Transportation*, Springer, 2016.

[4] IMO, *Fourth IMO GHG Study*, IMO, 2020.

[5] European Environmental Agency, *Emissions of air Pollutants from Transport*, 2020, https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-air-pollutants-8/transport-emissions-ofair-pollutants-8.

[6] IMO, *Marpol Annex VI and NTC 2008 with Guidelines for Implementation. Technical Report*, IMO, 2013.

[7] IMO, *UN Body Adopts Climate Change Strategy for Shipping*, 2018, http://www.imo.org/en/MediaCentre/PressBriefings/Pages/06GHGinitialstrategy.aspx.

[8] E. Lindstad and T. I. Bø, "Potential power setups, fuels and hull designs capable of satisfying future EEDI requirements," *Transportation Research Part D: Transport and Environment*, vol. 63, pp. 276–290, 2018.

[9] P. Liu, N. Bose, K. Chen, and Y. Xu, "Development and optimization of dual-mode propellers for renewable energy," *Renewable Energy*, vol. 119, pp. 566–576, 2018.

[10] M. Wen, D. Pacino, C. A. Kontovas, and H. N. Psaraftis, "Amultiple ship routing and speed optimization problem under time, cost and environmental objectives," *Transportation Research Part D: Transport and Environment*, vol. 52, pp. 303–321, 2017.

[11] J. Zheng, H. Zhang, L. Yin et al., "A voyage with minimal fuel consumption for cruise ships," *Journal of Cleaner Production*, vol. 215, pp. 144–153, 2019.

[12] A. Uusitalo, J. Nerg, A. Grönman, S. Nikkanen, and M. Elg, "Numerical analysis on utilizing excess steam for electricity production in cruise ships," *Journal of Cleaner Production*, vol. 209, pp. 424–438, 2019.

[13] Y. Yan, H. Zhang, Y. Long et al., "Multi-objective design optimization of combined cooling, heating and power system for cruise ship application," *Journal of Cleaner Production*, vol. 233, pp. 264–279, 2019.

[14] M. Al-Falahi, T. Tarasiuk, S. Jayasinghe, Z. Jin, H. Enshaei, and J. Guerrero, “AC ship microgrids: control and power management optimization,” *Energies*, vol. 11, p. 1458, 2018.

[15] F. Burel, R. Taccani, and N. Zuliani, “Improving sustainability of maritime transport through utilization of liquefied natural gas (LNG) for propulsion,” *Energy*, vol. 57, pp. 412–420, 2013.

[16] C. W. Mohd Noor, M. M. Noor, and R. Mamat, “Biodiesel as alternative fuel for marine diesel engine applications: a review,” *Renewable and Sustainable Energy Reviews*, vol. 94, pp. 127–142, 2018.

[17] S. Bengtsson, K. Andersson, and E. Fridell, “A comparative life cycle assessment of marine fuels liquefied natural gas and three other fossil fuels,” *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, vol. 225, pp. 97–110, 2011.

[18] Y. Zhou, N. Pavlenko, D. Rutherford, L. Osipova, and B. Comer, *The potential of liquid biofuels in reducing ship emissions. Technical Report*, International Council on Clean Transportation, 2020.

[19] H. Winnes, E. Fridell, and J. Moldanová, “Effects of marine exhaust gas scrubbers on gas and particle emissions,” *Journal of Marine Science and Engineering*, vol. 8, p. 299, 2020.

[20] M. Feenstra, J. Monteiro, J. T. van den Akker, M. R. Abu-Zahra, E. Gilling, and E. Goetheer, “Ship-based carbon capture onboard of diesel or LNG-fuelled ships,” *International Journal of Greenhouse Gas Control*, vol. 85, pp. 1–10, 2019.

[21] Z. Zhou, M. Benbouzid, J. F. Charpentier, F. Scuiller, and T. Tang, “A reviewof energy storage technologies for marine current energy systems,” *Renewable and Sustainable Energy Reviews*, vol. 18, pp. 390–400, 2013.

[22] H. Wang, N. L. Trivyza, F. Mylonopoulos, and E. Boulougouris, “Comparison of decarbonisation solutions for shipping: hydrogen, ammonia and batteries,” in *SNAME 14th International Marine Design Conference*, Vancouver, Canada, 2022http://onepetro.org/snameimdc/proceedings-pdf/IMDC22/2-IMDC22/D021S003R004/2961807/sname-imdc-2022-297.pdf/1.

[23] F. Baldi, S. Moret, K. Tammi, and F. Maréchal, “The role of solid oxide fuel cells in future ship energy systems,” *Energy*, vol. 194, article 116811, 2020.

[24] L. van Biert, M. Godjevac, K. Visser, and P. V. Aravind, “A review of fuel cell systems for maritime applications,” *Journal of Power Sources*, vol. 327, pp. 345–364, 2016.

[25] C. Ezgi, M. T. Çoban, and O. Selvi, “Design and thermodynamic analysis of an SOFC system for naval surface ship application,” *Journal of Fuel Cell Science and Technology*, vol. 10, 2013.

[26] G. V. Huerta, J. A. Jordán, M. Dragon, K. Leites, and S. Kabelac, “Exergy analysis of the diesel pre-reforming solid oxide fuel cell system with anode off-gas recycling in the SchIBZ project. Part I: modeling and validation,” *International Journal of Hydrogen Energy*, vol. 43, pp. 16684–16693, 2018.

[27] H. Sapra, J. Stam, J. Reurings et al., “Integration of solid oxide fuel cell and internal combustion engine for maritime applications,” *Applied Energy*, vol. 281, article 115854, 2021.

[28] M. Rivarolo, D. Rattazzi, and L. Magistri, “Best operative strategy for energy management of a cruise ship employing different distributed generation technologies,” *International Journal of Hydrogen Energy*, vol. 43, pp. 23500–23510, 2018.

[29] R. E. Rosli, A. B. Sulong, W. R. Daud et al., “A review of high-temperature proton exchange membrane fuel cell (HT-PEMFC) system,” *International Journal of Hydrogen Energy*, vol. 42, pp. 9293–9314, 2017.

[30] K. Selvam, Y. Komatsu, A. Sciazko, S. Kaneko, and N. Shikazono, “Thermodynamic analysis of 100% system fuel utilization solid oxide fuel cell (SOFC) system fueled with ammonia,” *Energy Conversion and Management*, vol. 249, article 114839, 2021.

[31] L. van Biert, T. Woudstra, M. Godjevac, K. Visser, and P. V. Aravind, “A thermodynamic comparison of solid oxide fuel cell-combined cycles,” *Journal of Power Sources*, vol. 397, pp. 382–396, 2018.

[32] A. Buonomano, F. Calise, M. D. D’Accadia, A. Palombo, and M. Vicidomini, “Hybrid solid oxide fuel cells-gas turbine systems for combined heat and power: A review,” *Applied Energy*, vol. 156, pp. 32–85, 2015.

[33] B. van Veldhuizen, *Fuel cell systems applied in expedition cruise ships – a comparative impact analysis. Technical Report*, Delft University of Technology, 2020.

[34] S. Harboe, A. Schreiber, N. Margaritis, L. Blum, O. Guillon, and N. H. Menzler, “Manufacturing cost model for planar 5 kWel SOFC stacks at Forschungszentrum Jülich,” *International Journal of Hydrogen Energy*, vol. 45, pp. 8015–8030, 2020.

[35] T. L. Skafte, J. Hjelm, P. Blennow, and C. Graves, “Quantitative review of degradation and lifetime of solid oxide cells and stacks,” in *Proceedings of the 12th European SOFC & SOE Forum*, pp. 5–8, Lucerne, Switzerland, 2016.

[36] C. H. Choi, S. Yu, I. S. Han et al., “Development and demonstration of PEM fuel-cell-battery hybrid system for propulsion of tourist boat,” *International Journal of Hydrogen Energy*, vol. 41, pp. 3591–3599, 2016.

[37] J. Markowski and I. Pielecha, “The potential of fuel cells as a drive source of maritime transport,” in *IOP Conference Series: Earth and Environmental Science*, Institute of Physics Publishing, 2019.

[38] Y. M. A. Welaya, M. Mosleh, and N. R. Ammar, “Thermodynamic analysis of a combined gas turbine power plant with a solid oxide fuel cell for marine applications,” *International Journal of Naval Architecture and Ocean Engineering*, vol. 5, pp. 529–545, 2013.

[39] P. C. Okonkwo, O. O. Ige, E. M. Barhoumi et al., “Platinum degradation mechanisms in proton exchange membrane fuel cell (PEMFC) system: a review,” *International Journal of Hydrogen Energy*, vol. 46, pp. 15850–15865, 2021.

[40] A. Choudhury, H. Chandra, and A. Arora, “Application of solid oxide fuel cell technology for power generation - A review,” *Renewable and Sustainable Energy Reviews*, vol. 20, pp. 430–442, 2013.

[41] I. Ritucci, K. Agersted, P. Zielke et al., “A Ba-free sealing glass with a high coefficient of thermal expansion and excellent interface stability optimized for SOFC/SOEC stack applications,” *International Journal of Applied Ceramic Technology*, vol. 15, pp. 1011–1022, 2018.

[42] Battelle Memorial Institute, *Manufacturing Cost Analysis of 100 and 250 kW Fuel Cell Systems for Primary Power and Combined Heat and Power Applications*, Technical Report, United States Department of Energy, 2016.

[43] T. Tronstad and L. Langfeldt, *Study on the use of fuel cells in shipping. Technical Report*, EMSA European Maritime Safety, 2017.

[44] N. Minh, J. Mizusaki, and S. C. Singhal, "Advances in solid oxide fuel cells: review of progress through three decades of the international symposia on solid oxide fuel cells," *ECS Transactions*, vol. 78, pp. 63–73, 2017.

[45] M. Singh, D. Zappa, and E. Comini, "Solid oxide fuel cell: decade of progress, future perspectives and challenges," *International Journal of Hydrogen Energy*, vol. 46, pp. 27643–27674, 2021.

[46] S. Roychoudhury and R. Mastanduno, "Balance of plant," in *fuel cells: technologies for Fuel processing*, Elsevier, 2011.

[47] J. G. Sung, T. Kim, H. K. Jung, H. Kim, and J. S. Chung, "Catalytic combustion of SOFC stack flue gas over CuO and Mn2O3 supported by La0.8Sr0.2Mn0.67Cu0.33O3 perovskite," *AIChE Journal*, vol. 64, pp. 940–949, 2018.

[48] O. van Rheinberg, K. Lucka, H. Köhne, T. Schade, and J. T. Andersson, "Selective removal of sulphur in liquid fuels for fuel cell applications," *Fuel*, vol. 87, pp. 2988–2996, 2008.

[49] V. Liso, A. C. Olesen, M. P. Nielsen, and S. K. Kær, "Performance comparison between partial oxidation and methane steam reforming processes for solid oxide fuel cell (SOFC) micro combined heat and power (CHP) system," *Energy*, vol. 36, pp. 4216–4226, 2011.

[50] F. Calise, M. D. d'Accadia, L. Vanoli, and M. R. von Spakovsky, "Full load synthesis/design optimization of a hybrid SOFC-GT power plant," *Energy*, vol. 32, pp. 446–458, 2007.

[51] F. Calise, A. Palombo, and L. Vanoli, "Design and partial load exergy analysis of hybrid SOFC-GT power plant," *Journal of Power Sources*, vol. 158, pp. 225–244, 2006.

[52] S. H. Chan, H. K. Ho, and Y. Tian, "Modelling for part-load operation of solid oxide fuel cell-gas turbine hybrid power plant," *Journal of Power Sources*, vol. 114, pp. 213–227, 2003.

[53] J. Jia, Q. Li, M. Luo, L. Wei, and A. Abudula, "Effects of gas recycle on performance of solid oxide fuel cell power systems," *Energy*, vol. 36, pp. 1068–1075, 2011.

[54] P. H. Wagner, Z. Wuillemin, D. Constantin, S. Diethelm, J. Van Herle, and J. Schiffmann, "Experimental characterization of a solid oxide fuel cell coupled to a steam-driven micro anode off-gas recirculation fan," *Applied Energy*, vol. 262, article 114219, 2020.

[55] L. van Biert, K. Visser, and P. V. Aravind, "A comparison of steam reforming concepts in solid oxide fuel cell systems," *Applied Energy*, vol. 264, article 114748, 2020.

[56] F. Schäfer, S. Egger, D. Steiner, M. Carré, and R. A. Eichel, "Control of oxygen-to-carbon ratio and fuel utilization with regard to solid oxide fuel cell systems with anode exhaust gas recirculation: A review," *Journal of Power Sources*, vol. 524, article 231077, 2022.

[57] T. S. Lee, J. N. Chung, and Y. C. Chen, "Design and optimization of a combined fuel reforming and solid oxide fuel cell system with anode off-gas recycling," *Energy Conversion and Management*, vol. 52, pp. 3214–3226, 2011.

[58] R. Peters, R. Deja, M. Engelbracht et al., "Efficiency analysis of a hydrogen-fueled solid oxide fuel cell system with anode off-gas recirculation," *Journal of Power Sources*, vol. 328, pp. 105–113, 2016.

[59] F. Zabihian and A. S. Fung, "Thermodynamic sensitivity analysis of hybrid system based on solid oxide fuel cell," *Sustainable Energy Technologies and Assessments*, vol. 6, pp. 51–59, 2014.

[60] J. Larminie and A. Dicks, *Fuel Cell Systems Explained*, Wiley, Second Edition edition, 2003.

[61] R. Peters, R. Deja, L. Blum, J. Pennanen, J. Kiviaho, and T. Hakala, "Analysis of solid oxide fuel cell system concepts with anode recycling," *International Journal of Hydrogen Energy*, vol. 38, pp. 6809–6820, 2013.

[62] J. Hollmann, M. Fuchs, E. Pohl et al., "Progress in the development of LNG and diesel-fueled SOFC systems for maritime applications," in *15th European SOFC & SOE Forum*, pp. 253–733, Lucerne, Switzerland, 2022.

[63] S. S. Kumar, N. C. Mukundan, P. Jayaprakash, and M. V. Kumar, "Grid tied solid oxide fuel cell power generation system for peak load management," in *International Conference on Electrical, Computer and Communication Technologies 3*, Coimbatore, India, 2019.

[64] X. Yu, M. R. Starke, L. M. Tolbert, and B. Ozpineci, "Fuel cell power conditioning for electric power applications: a summary," *IET Electric Power Applications*, vol. 1, pp. 643–656, 2007.

[65] L. Luckose, H. L. Hess, and B. K. Johnson, "Fuel cell propulsion system for marine applications," in *IEEE Electric Ship Technologies Symposium, ESTS 20069*, pp. 574–580, Baltimore, MD, USA, 2009.

[66] J. Ki and D. Kim, "Computational model to predict thermal dynamics of planar solid oxide fuel cell stack during startup process," *Journal of Power Sources*, vol. 195, pp. 3186–3200, 2010.

[67] U. Bossel, *Rapid Startup SOFC modules*, Energy Procedia, Elsevier Ltd., 2012.

[68] C. Stiller, *Design, Operation and Control Modelling of SOFC/GT Hybrid Systems. Technical Report*, Norwegian University of Science and Technology, Trondheim, 2006, https://ntnuopen.ntnu.no/ntnuxmlui/handle/11250/231300.

[69] F. Baldi, L. Wang, M. Pérez-Fortes, and F. Maréchal, "A cogeneration system based on solid oxide and proton exchange membrane fuel cells with hybrid storage for off-grid applications," *Frontiers in Energy Research*, vol. 6, p. 139, 2019.

[70] L. Tan, C. Yang, and N. Zhou, "Thermoeconomic optimization of a solid oxide fuel cell and proton exchange membrane fuel cell hybrid power system," *Journal of Fuel Cell Science and Technology*, vol. 11, 2014.

[71] L. Tan, C. Yang, and N. Zhou, "Synthesis/design optimization of SOFCPEM hybrid system under uncertainty," *Chinese Journal of Chemical Engineering*, vol. 23, pp. 128–137, 2015.

[72] A. Hagen, R. Caldogno, and X. Sun, "Ammonia fueled SOFC for shipping– the Aegir project," in *15th European SOFC & SOE Forum*, pp. 5–8, Lucerne, Switzerland, 2022.

[73] H. Sapra, *Combined gas engine- solid oxide fuel cell systems for marine power generation, [Ph.D. thesis]*, Ship Design, Production and Operations, 2020.

[74] Y. Kawabata, D. Takeda, K. Ochi et al., "Practicality evaluation of solid oxide fuel cell (SOFC) - micro gas turbine (MGT) hybrid power generation system," in *Proceedings of 14th European SOFC & SOE Forum*, pp. 132–143, Lucerne, Switzerland, 2020.

[75] D. P. Bakalis and A. G. Stamatis, "Incorporating available micro gas turbines and fuel cell: matching considerations and performance evaluation," *Applied Energy*, vol. 103, pp. 607–617, 2013.

[76] L. Barelli, G. Bidini, and A. Ottaviano, "Part load operation of SOFC/GT hybrid systems: stationary analysis," *International Journal of Hydrogen Energy*, vol. 37, pp. 16140–16150, 2012.

[77] Y. Komatsu, S. Kimijima, and J. S. Szmyd, “Performance analysis for the part-load operation of a solid oxide fuel cell-micro gas turbine hybrid system,” *Energy*, vol. 35, pp. 982–988, 2010.

[78] J. Chen, Y. Chen, H. Zhang, and S. Weng, “Effect of different operating strategies for a SOFC-GT hybrid system equipped with anode and cathode ejectors,” *Energy*, vol. 163, pp. 1–14, 2018.

[79] F. D. F. Chuahy and S. L. Kokjohn, “Solid oxide fuel cell and advanced combustion engine combined cycle: A pathway to 70% electrical efficiency,” *Applied Energy*, vol. 235, pp. 391–408, 2019.

[80] Y. M. A. Welaya, M. Mosleh, and N. R. Ammar, “Energy analysis of a combined solid oxide fuel cell with a steam turbine power plant for marine applications,” *Journal of Marine Science and Application*, vol. 12, pp. 473–483, 2014.

[81] A. Arsalis, “Thermoeconomic modeling and parametric study of hybrid SOFC-gas turbine-steam turbine power plants ranging from 1.5 to 10 MWe,” *Journal of Power Sources*, vol. 181, no. 2, pp. 313–326, 2008.

[82] Z. Wu, P. Zhu, J. Yao et al., “Dynamic modeling and operation strategy of natural gas fueled SOFC-engine hybrid power system with hydrogen addition by metal hydride for vehicle applications,” *eTransportation*, vol. 5, article 100074, 2020.

[83] Chevron Global Marine Products, *Everything You Need to Know About Marine Fuels. Technical Report*, Chevron Global Marine Products, Ghent, 2012.

[84] P. Boldrin, E. Ruiz-Trejo, J. Mermelstein, J. M. Bermúdez Menéndez, T. RamÍrez Reina, and N. Brandon, “Strategies for carbon and sulfur tolerant solid oxide fuel cell materials, incorporating lessons from heterogeneous catalysis,” *Chemical Reviews*, vol. 116, no. 22, pp. 13633–13684, 2016.

[85] D. N. Kuimov, M. S. Minkin, and A. D. Lukyanov, “Low-sulfur fuel and oil production,” *Materials Science Forum*, vol. 870, pp. 671–676, 2016.

[86] Y. Shiratori, T. Quang-Tuye, and K. Sasaki, “Performance enhancement of biodiesel fueled SOFC using paper-structured catalyst,” *International Journal of Hydrogen Energy*, vol. 38, pp. 9856–9866, 2013.

[87] A. Kumar and S. Sharma, “Potential non-edible oil resources as biodiesel feedstock: an Indian perspective,” *Renewable and Sustainable Energy Reviews*, vol. 15, pp. 1791–1800, 2011.

[88] M. C. Díaz-de Baldasano, F. J. Mateos, L. R. Núñez-Rivas, and T. J. Leo, “Conceptual design of offshore platform supply vessel based on hybrid diesel generator-fuel cell power plant,” *Applied Energy*, vol. 116, pp. 91–100, 2014.

[89] P. Nehter, B. Wildrath, A. Bauschulte, and K. Leites, “Diesel based SOFC demonstrator for maritime applications,” *ECS Transactions*, vol. 78, pp. 171–180, 2017.

[90] L. Van Hoecke, L. Laffineur, R. Campe, P. Perreault, S. W. Verbruggen, and S. Lenaerts, “Challenges in the use of hydrogen for maritime applications,” *Energy & Environmental Science*, vol. 14, no. 2, pp. 815–843, 2021.

[91] R. A. Evrin and I. Dincer, “Thermodynamic analysis and assessment of an integrated hydrogen fuel cell system for ships,” *International Journal of Hydrogen Energy*, vol. 44, pp. 6919–6928, 2019.

[92] P. Kazempoor, V. Dorer, and F. Ommi, “Evaluation of hydrogen and methane-fuelled solid oxide fuel cell systems for residential applications: System design alternative and parameter study,” *International Journal of Hydrogen Energy*, vol. 34, pp. 8630–8644, 2009.

[93] L. Wang, Y. Zhang, M. Pérez-Fortes et al., “Reversible solid-oxide cell stack based power-to-x-to-power systems: comparison of thermodynamic performance,” *Applied Energy*, vol. 275, article 115330, 2020.

[94] M. M. F. Hasan, A. M. Zheng, and I. A. Karimi, “Minimizing boil-off losses in liquefied natural gas transportation,” *Industrial and Engineering Chemistry Research*, vol. 48, pp. 9571–9580, 2009.

[95] International Gas Union, *2020World LNGReport. Technical Report*, 2020, https://igu.org/resources/2020-world-lng-report/.

[96] P. Balcombe, J. Brierley, C. Lewis et al., “Howto decarbonise international shipping: options for fuels, technologies and policies,” *Energy Conversion and Management*, vol. 182, pp. 72–88, 2019.

[97] T. M. Gür, “Comprehensive review of methane conversion in solid oxide fuel cells: Prospects for efficient electricity generation from natural gas,” *Progress in Energy and Combustion Science*, vol. 54, pp. 1–64, 2016.

[98] R. Payne, J. Love, and M. Kah, “Generating electricity at 60% electrical efficiency from 1-2 kWe SOFC products,” *ECS Transactions*, vol. 25, pp. 231–239, 2009.

[99] S. A. Saadabadi, A. Thallam Thattai, L. Fan, R. E. F. Lindeboom, H. Spanjers, and P. V. Aravind, “Solid Oxide Fuel Cells Fuelled with Biogas: Potential and Constraints,” *Renewable Energy*, vol. 134, pp. 194–214, 2019.

[100] I. Ridjan, *Integrated electrofuels and renewable energy systems, [Ph.D. thesis]*, Aalborg University, 2015, https://www.researchgate.net/publication/292708910_Integrated_electrofuels_and_renewable_energy_systems.

[101] D. Cocco and V. Tola, “Externally reformed solid oxide fuel cell-microgas turbine (SOFC-MGT) hybrid systems fueled by methanol and dimethyl-ether (DME),” *Energy*, vol. 34, pp. 2124–2130, 2009.

[102] J. Rechberger, R. Schauperl, J. B. Hansen, and P. K. Larsen, “Development of a methanol SOFC APU demonstration system,” *ECS Transactions*, vol. 25, pp. 1085–1092, 2009.

[103] N. Laosiripojana and S. Assabumrungrat, “Catalytic steam reforming of methane, methanol, and ethanol over Ni/YSZ: The possible use of these fuels in internal reforming SOFC,” *Journal of Power Sources*, vol. 163, pp. 943–951, 2007.

[104] M. Liu, R. Peng, D. Dong, J. Gao, X. Liu, and G. Meng, “Direct liquid methanol-fueled solid oxide fuel cell,” *Journal of Power Sources*, vol. 185, pp. 188–192, 2008.

[105] Q. Xu and M. Ni, “Modelling of high temperature direct methanol solid oxide fuel cells,” *International Journal of Energy Research*, vol. 45, pp. 3097–3112, 2021.

[106] J. Ellis and K. Tanneberger, *Study on the use of ethyl and methyl alcohol as alternative fuels in shipping. Technical Report. EMSA*, 2016, http://www.emsa.europa.eu/news-a-press-centre/external-news/item/2726-study-on-the-use-of-ethyl-and-methyl-alcohol-as-alternativefuels-in-shipping.html.

[107] K. Moirangthem and D. Baxter, *Alternative fuels for marine and inland waterways. Technical Report*, JRC, 2016.

[108] C. Su, R. Ran, W. Wang, and Z. Shao, “Coke formation and performance of an intermediate-temperature solid oxide fuel cell operating on dimethyl ether fuel,” *Journal of Power Sources*, vol. 196, pp. 1967–1974, 2011.

[109] E. P. Murray, S. J. Harris, and H. Jen, "Solid oxide fuel cells utilizing dimethyl ether fuel," *Journal of The Electrochemical Society*, vol. 149, p. A1127, 2002.

[110] K. Sato, Y. Tanaka, A. Negishi, and T. Kato, "Dual fuel type solid oxide fuel cell using dimethyl ether and liquefied petroleum gas as fuels," *Journal of Power Sources*, vol. 217, pp. 37–42, 2012.

[111] M. Cheliotis, E. Boulougouris, N. L. Trivyza et al., "Review on the safe use of ammonia fuel cells in the maritime industry," *Energies*, vol. 14, p. 3023, 2021.

[112] A. Afif, N. Radenahmad, Q. Cheok, S. Shams, J. H. Kim, and A. K. Azad, "Ammonia-fed fuel cells: a comprehensive review," *Renewable and Sustainable Energy Reviews*, vol. 60, pp. 822–835, 2016.

[113] L. van Biert, *Solid Oxide Fuel Cells for Ships, [Ph.D. thesis]*, Delft University of Technology, 2020.

[114] Z. Wan, Y. Tao, J. Shao, Y. Zhang, and H. You, "Ammonia as an effective hydrogen carrier and a clean fuel for solid oxide fuel cells," *Energy Conversion and Management*, vol. 228, article 113729, 2021.

[115] Q. Ma, R. R. Peng, L. Tian, and G. Meng, "Direct utilization of ammonia in intermediate-temperature solid oxide fuel cells," *Electrochemistry Communications*, vol. 8, pp. 1791–1795, 2006.

[116] M. Ni, M. K. H. Leung, and D. Y. C. Leung, "Ammonia-fed solid oxide fuel cells for power generation-a review," *International Journal of Energy Research*, vol. 33, no. 11, pp. 943–959, 2009.

[117] L. Barelli, G. Bidini, and G. Cinti, "Operation of a solid oxide fuel cell based power system with ammonia as a fuel: experimental test and system design," *Energies*, vol. 13, 2020.

[118] G. Cinti, G. Discepoli, E. Sisani, and U. Desideri, "SOFC operating with ammonia: stack test and system analysis," *International Journal of Hydrogen Energy*, vol. 41, pp. 13583–13590, 2016.

[119] H. L. Frandsen, H. Nami, O. B. Rizvandi et al., "Operation and modelling of ammonia fuelled solid oxide fuel cell , stack and systems," in *15th European SOFC & SOE Forum*, pp. 314–321, Delft, 2022.

[120] S. M. Aceves, F. Espinosa-Loza, E. Ledesma-Orozco et al., "High-density automotive hydrogen storage with cryogenic capable pressure vessels," *International Journal of Hydrogen Energy*, vol. 35, pp. 1219–1226, 2010.

[121] B. N. van Veldhuizen, R. G. Hekkenberg, and L. Codiglia, "Fuel cell systems applied in expedition cruise ships – a comparative impact analysis," in *HIPER*, Delft University of Technology, 2020.

[122] L. Xiang, E. Song, and Y. Ding, "A two-zone combustion model for knocking prediction of marine natural gas SI engines," *Energies*, vol. 11, p. 561, 2018.

[123] K. Cheenkachorn, C. Poompipatpong, and C. G. Ho, "Performance and emissions of a heavy-duty diesel engine fuelled with diesel and LNG (liquid natural gas)," *Energy*, vol. 53, pp. 52–57, 2013.

[124] H. Pan, S. Pournazeri, M. Princevac et al., "Effect of hydrogen addition on criteria and greenhouse gas emissions for a marine diesel engine," *International Journal of Hydrogen Energy*, vol. 39, pp. 11336–11345, 2014.

[125] S. Campanari, *Full Load and part-load performance prediction for integrated SOFC and microturbine systems. Technical Report*, 2000, http://asmedigitalcollection.asme.org/gasturbinespower/article-pdf/122/2/239/5636334/239_1.pdf.

[126] K. Levander, *System based ship design*, SeaKey Naval Architecture, 2007.

[127] R. Geertsma and M. Krijgsman, *Alternative Fuels and Power Systems to Reduce Environmental Impact of Support Vessels*, Delft University of Technology, 2019.

[128] B. Taskar, K. K. Yum, S. Steen, and E. Pedersen, "The effect of waves on engine-propeller dynamics and propulsion performance of ships," *Ocean Engineering*, vol. 122, pp. 262–277, 2016.

[129] F. Baldi, F. Ahlgren, T. Nguyen, M. Thern, and K. Andersson, "Energy and Exergy Analysis of a Cruise Ship," *Energies*, vol. 11, p. 2508, 2018.

[130] Y. M. A. Welaya, M. M. El Gohary, and N. R. Ammar, "A comparison between fuel cells and other alternatives for marine electric power generation," *International Journal of Naval Architecture and Ocean Engineering*, vol. 3, pp. 141–149, 2011.

[131] R. Scataglini, M. Wei, A. Mayyas, S. H. Chan, T. Lipman, and M. Santarelli, "A Direct Manufacturing Cost Model for Solid-Oxide Fuel Cell Stacks," *Fuel Cells*, vol. 17, pp. 825–842, 2017.

[132] EGG technical services, *Fuel Cell Handbook (Seventh Edition)*, EGG technical services, 2004.

[133] M. Suzuki, S. Inoue, and T. Shigehisa, "Field test result of residential SOFC CHP system over 10 years, 89000 hours," *ECS Transactions*, vol. 103, no. 1, pp. 25–30, 2021.

[134] C. M. Milkie and A. N. Perakis, "Statistical methods for planning diesel engine overhauls in the US Coast Guard," *Naval Engineers Journal*, vol. 116, no. 2, pp. 31–42, 2004.

[135] D. Woodyard, *Pounder's Marine Diesel Engines and Gas Turbines*, 2009, https://books.google.nl/books?hl=nl&lr=&id=RC_k4q6y-JIC&oi=fnd&pg=PP1&dq=marine+diesel+generator+hours+to+maintenance+overhaul&ots=rD1JzvVENT&sig=6irCO8Jr55MkODXQvO-hVO_ikPM&redir_esc=y#v=snippet&q=TBO&f=false.

[136] N. Jones, "Ocean uproar: saving marine life from a barrage of noise," *Nature*, vol. 568, pp. 158–162, 2019.

[137] M. Rivarolo, D. Rattazzi, L. Magistri, and A. F. Massardo, "Multicriteria comparison of power generation and fuel storage solutions for maritime application," *Energy Conversion and Management*, vol. 244, article 114506, 2021.

[138] M. Archetti, E. Audasso, B. Bosio, and D. Bove, "High temperature fuel cells to reduce CO2 emission in the maritime sector," in *E3S Web of Conferences*, vol. 334, p. 04013, EDP Sciences, 2022.

[139] A. Haseltalab, L. van Biert, H. Sapra, B. Mestemaker, and R. R. Negenborn, "Component sizing and energy management for SOFC-based ship power systems," *Energy Conversion and Management*, vol. 245, article 114625, 2021.

[140] O. Chaves, M. Nickelsen, and H. Gaspar, "Enhancing Virtual Prototype in Ship Design Using Modular Techniques," in *29th European Conference on Modelling and Simulation*, Albena, Bulgaria, 2015.

[141] S. O. Erikstad, *Modularisation in Shipbuilding and Modular Production*, 2009, https://www.researchgate.net/publication/267375279.

[142] S. Pekic, *GTT's LNG containment system to be used for ammonia*, 2021, https://www.offshore-energy.biz/gtts-lng-containmentsystem-to-be-used-for-ammonia/.

[143] D. Sahnen, *Key Aspects for New ship Fuels*, Methanol Day, 2020.

[144] J. Ahn, S. H. Park, Y. Noh et al., "Performance and availability of a marine generator-solid oxide fuel cell-gas turbine hybrid system in a very large ethane carrier," *Journal of Power Sources*, vol. 399, pp. 199–206, 2018.

[145] C. Bang-Møller, M. Rokni, B. Elmegaard, J. Ahrenfeldt, and U. B. Henriksen, "Decentralized combined heat and power production by twostage biomass gasification and solid oxide fuel cells," *Energy*, vol. 58, pp. 527–537, 2013.

[146] L. Kistner, A. Bensmann, and R. Hanke-Rauschenbach, "Optimal design of a distributed ship power system with solid oxide fuel cells under the consideration of component malfunctions," *Applied Energy*, vol. 316, article 119052, 2022.

[147] M. R. Barakat, B. Tala-Ighil, H. Gualous, and D. Hissel, "JADE-based multi-agent decentralized energy management system of a hybrid marine-hydrogen power generation system," in *Lecture Notes in Electrical Engineering*, pp. 245–257, Springer, Cham, 2020.

[148] K. Leites, S. Krummrich, P. Nehter, A. Bauschulte, N. Kleinohl, and W. Kühnau, "SchIBZ – Application of solid oxide fuel cells for oceangoing ships SchIBZ," in *Conference on Fundamentals and Development of Fuel Cells*, Karlsruhe, Germany, 2013.

[149] W. S. Weidle, P. Field, and N. Buckley, *Arctic Ship Design Impacts: Green Arctic Patrol Vessel (GAPV) Project. Technical Report*, Naval Surface Warfare Center, 2012.

[150] L. Cohen, A. Tate, and N. Weinhold, *Investigation into the Implications of Fuel Cell Shipboard Integration into the T-AGOS 19 Class. Technical Report*, 2012, https://apps.dtic.mil/sti/citations/ADA558631.

[151] DNVGL-CG, *Guidance for safe return to port projects. Technical Report*, DNVGL-CG, 2016.

[152] L. Micoli, T. Coppola, and M. Turco, "A Case study of a solid oxide fuel cell plant on board a cruise ship," *Journal of Marine Science and Application*, vol. 20, pp. 524–533, 2021.

[153] G. Chang, Y. Wu, S. Shao, Z. Huang, and T. Long, "Dc bus systems for electrical ships: recentAdvances and analysis of a real case," *IEEE Electrification Magazine*, vol. 8, pp. 28–39, 2020.

[154] C. Nuchturee, T. Li, and H. Xia, "Energy efficiency of integrated electric propulsion for ships-A review," *Renewable and Sustainable Energy Reviews*, vol. 134, 2020.

[155] J. F. Hansen, J. O. Lindtjørn, U. U. Ødegaard, and T. A. Myklebust, "Increased operational performance of OSVs by onboard DC grid," in *4th International Conference on Technology and Operation of Offshore Support Vessels*, pp. 79–84, Singapore, 2011.

[156] B. Zahedi, L. E. Norum, and K. B. Ludvigsen, "Optimized efficiency of all-electric ships by dc hybrid power systems," *Journal of Power Sources*, vol. 255, pp. 341–354, 2014.

[157] F. D. Kanellos, G. J. Tsekouras, and J. Prousalidis, "Onboard DC grid employing smart grid technology: challenges, state of the art and future prospects," *IET Electrical Systems in Transportation*, vol. 5, pp. 1–11, 2015.

[158] S. Yadav, N. H. Van Der Blii, and P. Bauer, "Modeling and stability analysis of radial and zonal architectures of a bipolar DC ferry ship," in *2021 IEEE Electric Ship Technologies Symposium, ESTS 2021*, Arlington, VA, USA, 2021.

[159] IEEE, *IEEE Recommended Practice for 1 kV to 35 kV Medium-Voltage DC Power Systems on Ships. Technical Report*, IEEE, New York, 2018.

[160] S. Habib, M. M. Khan, F. Abbas et al., "Contemporary trends in power electronics converters for charging solutions of electric vehicles," *CSEE Journal of Power and Energy Systems*, vol. 6, pp. 911–929, 2020.

[161] A. M. Bassam, A. B. Phillips, S. R. Turnock, and P. A. Wilson, "Development of a multi-scheme energy management strategy for a hybrid fuel cell driven passenger ship," *International Journal of Hydrogen Energy*, vol. 42, pp. 623–635, 2017.

[162] R. Fang, W. Jiang, J. Khan, and R. Dougal, "System-level thermal modeling and co-simulation with hybrid power system for future all electric ship," in *2009 IEEE Electric Ship Technologies Symposium*, pp. 547–553, Baltimore, MD, 2009.

[163] L. K. C. Tse, S. Wilkins, N. McGlashan, B. Urban, and R. Martinez-Botas, "Solid oxide fuel cell/gas turbine trigeneration system for marine applications," *Journal of Power Sources*, vol. 196, pp. 3149–3162, 2011.

[164] P. A. Duong, B. Ryu, C. Kim, J. Lee, and H. Kang, "Energy and exergy analysis of an ammonia fuel cell integrated system for marine vessels," *Energies*, vol. 15, p. 3331, 2022.

[165] ABS, *Guide for fuel cell power systems for marine and offshore applications*, Technical Report. American Bureau of Shipping, New York, 2019.

[166] DNVGL-CG, "Fuel cell installations," in *DNVGL rules for classification of ships. Chapter Part 6 Cha*, DNVGL-CG, 2019.

[167] M. Gianni, A. Pietra, and R. Taccani, "Outlook of future implementation of PEMFC and SOFC onboard cruise ships," *E3S Web of Conferences*, vol. 238, p. 04004, 2021.

[168] M. Sharifzadeh, M. Meghdari, and D. Rashtchian, "Multi-objective design and operation of solid oxide fuel cell (SOFC) triple combinedcycle power generation systems: integrating energy efficiency and operational safety," *Applied Energy*, vol. 185, pp. 345–361, 2017.

[169] H. Xing, C. Stuart, S. Spence, and H. Chen, "Fuel cell power systems for maritime applications: progress and perspectives," *Sustainability (Switzerland)*, vol. 13, pp. 1–34, 2021.

[170] DNVGL-CG, *Shipping 2020. Technical Report*, DNVGL-CG, 2012.

[171] S. D. Micco, M. Minutillo, L. Mastropasqua, V. Cigolotti, and J. Brouwer, "Ammonia-based Solid Oxide Fuel Cell for zero emission maritime power: a case study," *E3S Web of Conferences*, vol. 334, p. 06007, 2021.

[172] K. Kim, G. Roh, W. Kim, and K. Chun, "A preliminary study on an alternative ship propulsion system fueled by ammonia: environmental and economic assessments," *Journal of Marine Science and Engineering*, vol. 8, p. 183, 2020.

[173] L. Kistner, F. L. Schubert, C. Minke, A. Bensmann, and R. Hanke-Rauschenbach, "Techno-economic and environmental comparison of internal combustion engines and solid oxide fuel cells for ship applications," *Journal of Power Sources*, vol. 508, article 230328, 2021.

[174] C. Strazza, A. Del Borghi, P. Costamagna, A. Traverso, and M. Santin, "Comparative LCA of methanol-fuelled SOFCs as auxiliary power systems on-board ships," *Applied Energy*, vol. 87, pp. 1670–1678, 2010.

[175] M. Altmann, W. Weindorf, R. Wurster, M. Weinberger, and G. Filip, "FCSHIP: Environmental Impacts and Costs of Hydrogen, Natural Gas and Conventional Fuels for Fuel Cell

Ships," in *15th World Hydrogen Energy Conference*, Yokohama, Japón, 2004.

[176] Y. D. Lee, K. Y. Ahn, T. Morosuk, and G. Tsatsaronis, "Environmental impact assessment of a solid-oxide fuel-cell-based combined-heat-andpower-generation system," *Energy*, vol. 79, pp. 455–466, 2015.

[177] A. Mehmeti, S. J. McPhail, D. Pumiglia, and M. Carlini, "Life cycle sustainability of solid oxide fuel cells: From methodological aspects to system implications," *Journal of Power Sources*, vol. 325, pp. 772–785, 2016.

[178] Y. Bicer and F. Khalid, "Life cycle environmental impact comparison of solid oxide fuel cells fueled by natural gas, hydrogen, ammonia and methanol for combined heat and power generation," *International Journal of Hydrogen Energy*, vol. 45, pp. 3670–3685, 2020.

[179] M. Perčić, N. Vladimir, I. Jovanović, and M. Koričan, "Application of fuel cells with zero-carbon fuels in short-sea shipping," *Applied Energy*, vol. 309, article 118463, 2022.

[180] S. Sarner, N. H. Menzler, A. Mai, D. Sergeev, N. Margaritis, and O. Guillon, "Recycling possibilities and strategies for solid oxide cell stacks," in *15th European SOFC & SOE Forum*, pp. 714–718, Lucerne, Switzerland, 2022.

[181] FELICITAS, *Publishable Final Activity Report. Technical Report*, Fraunhofer Institute for Transportation and Infrastructure Systems, 2009.

[182] METHAPU, *Publishable Executive Summary. Technical Report*, 2010, https://trimis.ec.europa.eu/project/validation-renewablemethanol-based-auxiliary-power-system-commercial-vessels#taboutline.

[183] Fuel Cells Bulletin, "Sunfire 50 kW SOFC for ship-integrated fuel cell project in Germany," *Fuel Cells Bulletin*, vol. 2015, pp. 3-4, 2015.

[184] Fuel Cells Bulletin, *MultiSchiBZ project on SOFCs for onboard clean power for ships*, Fuel Cells Bulletin, 2019.

[185] G. V. Huerta, J. A. Jordán, T. Marquardt, M. Dragon, K. Leites, and S. Kabelac, "Exergy analysis of the diesel pre-reforming SOFC-system with anode off-gas recycling in the SchIBZ project. Part II: system exergetic evaluation," *International Journal of Hydrogen Energy*, vol. 44, pp. 10916–10924, 2019.

[186] J. Hollmann, M. Fuchs, C. Spieker et al., "System simulation and analysis of an LNG-fueled SOFC system using additively manufactured high temperature heat exchangers," *Energies*, vol. 15, p. 941, 2022.

[187] M. Metten, S. S. Ventura, D. Ullmer et al., "Evaluation of a hybrid SOFC & battery genset for cruise ship applications," in *15th European SOFC & SOE Forum*, pp. 612–620, Switzerland, Lucerne, 2022.

[188] S. A. Ansar, M. Metten, S. S. Ventura, D. Ullmer, and C. Schnegelberger, "Electrochemical processes and energy systems towards step-wise emission reduction of the marine sector," in *15th European SOFC & SOE Forum*, pp. 672–678, Switzerland, Lucerne, 2022.

[189] CORDIS, *Nautical Integrated Hybrid Energy System for Long-haul Cruise Ships*, 2020, https://cordis.europa.eu/project/id/861647.

[190] C. Bettini, I. Wærnhus, T. M. Svendsen et al., "ShipFC project: NH3-SOFC to decarbonise commercial shipping applications," in *15th European SOFC & SOE Forum*, pp. 660–671, Lucerne, Switzerland, 2022.

[191] OpenAIRE, *HELENUS*, 2022, https://explore.openaire.eu/search/project?projectId=corda_____he::ddc12658363be9e7447374434a0cbb90.

[192] R. R. Liu, S. H. Kim, S. Taniguchi et al., "Influence of water vapor on long-term performance and accelerated degradation of solid oxide fuel cell cathodes," *Journal of Power Sources*, vol. 196, pp. 7090–7096, 2011.

[193] A. Hagen, K. Neufeld, and Y. L. Liu, "Effect of humidity in air on performance and long-term durability of SOFCs," *Journal of The Electrochemical Society*, vol. 157, p. B1343, 2010.

[194] Z. Yang, M. Guo, N. Wang, C. Ma, J. Wang, and M. Han, "A short review of cathode poisoning and corrosion in solid oxide fuel cell," *International Journal of Hydrogen Energy*, vol. 42, pp. 24948–24959, 2017.

[195] R. R. Liu, D. J. Wang, and J. Leng, "Influence of NaCl on cathode performance of solid oxide fuel cells," *Chemical Research in Chinese Universities*, vol. 29, pp. 747–750, 2013.

[196] N. Thambiraj, C. Suciu, I. Waernhus, A. Vik, and A. C. Hoffmann, "SOFC cathode degradation due to salt contamination," *ECS Meeting Abstracts*, vol. 78, pp. 915–925, 2017.

[197] J. W. Fergus, "Effect of water vapor and hydrogen on the oxidation of metallic interconnect materials for solid oxide fuel cells," *ECS Proceedings Volumes*, vol. 2005, pp. 1806–1815, 2005.

[198] K. Yoshimoto, Y. Hirata, and M. Chiba, *Salt in Sea Atmosphere and Its Removal for Gas Turbines*, American Society of Mechanical Engineers (Paper), 1976.

[199] G. D. Agnew, N. T. Hart, G. J. Wright et al., "Scale Up of a Multi-Functional Solid Oxide Fuel Cell to Multi-Tens of Kilowatt Level (MF-SOFC)," *ECS Proceedings*, vol. 2003, no. 1, p. 78, 2003.

[200] E. Ivers-Tiffée, A. Weber, and D. Herbstritt, "Materials and technologies for SOFC-components," *Journal of the European Ceramic Society*, vol. 21, pp. 1805–1811, 2001.

[201] D. Udomsilp, J. Rechberger, R. Neubauer et al., "Metal-supported solid oxide fuel cells with exceptionally high power density for range extender systems," *Cell Reports Physical Science*, vol. 1, article 100072, 2020.

[202] A. Hagen, A. C. Wulff, P. Zielke et al., "SOFC stacks for mobile applications with excellent robustness towards thermal stresses," *International Journal of Hydrogen Energy*, vol. 45, pp. 29201–29211, 2020.

[203] M. Z. Khan, A. Iltaf, H. A. Ishfaq et al., "Flattubular solid oxide fuel cells and stacks: a review," *Journal of Asian Ceramic Societies*, vol. 9, pp. 745–770, 2021.

[204] J. H. Kim, R. H. Song, K. S. Song, S. H. Hyun, D. R. Shin, and H. Yokokawa, "Fabrication and characteristics of anode-supported flat-tube solid oxide fuel cell," *Journal of Power Sources*, vol. 122, pp. 138–143, 2003.

[205] M. Ilbas, M. Asmare Alemu, and F. Mustafa Cimen, "Comparative performance analysis of a direct ammonia-fuelled anode supported flat tubular solid oxide fuel cell: a 3D numerical study," *International Journal of Hydrogen Energy*, vol. 47, pp. 3416–3428, 2022.

[206] H. Ghezel-Ayagh, "Progress in SOFC technology development at fuelCell energy," in *20th Annual Solid Oxide Fuel Cell (SOFC), Project Review Meeting*, Washington, DC, 2019.

[207] B. V. Veldhuizen, L. V. Biert, and K. Visser, "Comparative thermodynamic analysis of marine SOFC system for alternative fuels," in *15th European SOFC & SOE Forum*, pp. 340–918, Lucerne, Switzerland, 2022.

[208] M. Promsen, Y. Komatsu, A. Sciazko, S. Kaneko, and N. Shikazono, "Feasibility study on saturated water cooled solid oxide fuel cell stack," *Applied Energy*, vol. 279, article 115803, 2020.

[209] V. M. Janardhanan, V. Heuveline, and O. Deutschmann, "Performance analysis of a SOFC under direct internal reforming conditions," *Journal of Power Sources*, vol. 172, pp. 296–307, 2007.

[210] M. Gandiglio, A. Lanzini, and M. Santarelli, "Large stationary solid oxide fuel cell (SOFC) power plants," in *Modeling, Design, Construction, and Operation of Power Generators with Solid Oxide Fuel Cells*, pp. 233–261, Springer Verlag, 2018.

[211] N. Mahato, A. Banerjee, A. Gupta, S. Omar, and K. Balani, "Progress in material selection for solid oxide fuel cell technology: a review," *Progress in Materials Science*, vol. 72, pp. 141–337, 2015.

[212] A. Pesaran, A. Jaiswal, Y. Ren, and E. D. Wachsman, "Development of a new ceria/yttria-ceria double-doped bismuth oxide bilayer electrolyte low-temperature SOFC with higher stability," *Ionics*, vol. 25, pp. 3153–3164, 2019.

[213] L. van Biert, M. Godjevac, K. Visser, and P. V. Aravind, "Dynamic modelling of a direct internal reforming solid oxide fuel cell stack based on single cell experiments," *Applied Energy*, vol. 250, pp. 976–990, 2019.

[214] M. Kusnezoff, N. Trofimenko, M. Müller, and A. Michaelis, "Influence of electrode design and contacting layers on performance of electrolyte supported SOFC/SOEC single cells," *Materials*, vol. 9, p. 906, 2016.

[215] O. Aydin, A. Kubota, D. L. Tran, M. Sakamoto, and Y. Shiratori, "Designing graded catalytic domain to homogenize temperature distribution while dry reforming of CH4," *International Journal of Hydrogen Energy*, vol. 43, pp. 17431–17443, 2018.

[216] X. Wang, K. Wei, J. Kang et al., "Experimental and numerical studies of a bifunctional proton conducting anode of ceria-based SOFCs free from internal shorting and carbon deposition," *Electrochimica Acta*, vol. 264, pp. 109–118, 2018.

[217] A. Lanzini, D. Ferrero, D. Papurello, and M. Santarelli, "Reporting degradation from different Fuel contaminants in Ni-anode SOFCs," *Fuel Cells*, vol. 17, pp. 423–433, 2017.

[218] S. C. Paulson and V. I. Birss, "Chromium poisoning of LSM-YSZ SOFC cathodes: I. Detailed study of the distribution of chromium species at a porous, single-phase cathode," *Journal of the Electrochemical Society*, vol. 151, pp. A1961–A1968, 2004.

[219] C. Laing, B. Hu, A. N. Aphale, M. B. Venkataraman, M. K. Mahapatra, and P. Singh, "Mitigation of chromium assisted degradation of LSM cathode in SOFC," *ECS Transactions*, vol. 75, no. 28, p. 57, 2017.

[220] T. Norgaard, "Scenarios for uptake of alternative fuels in the marine industry," in *World Marine Technology Conference*, Bergen, Norway, 2022.

[221] Y. Bae, S. Lee, K. J. Yoon, J. H. Lee, and J. Hong, "Three-dimensional dynamic modeling and transport analysis of solid oxide fuel cells under electrical load change," *Energy Conversion and Management*, vol. 165, pp. 405–418, 2018.

[222] T. Parhizkar and S. Hafeznezami, "Degradation based operational optimization model to improve the productivity of energy systems, case study: solid oxide fuel cell stacks," *Energy Conversion and Management*, vol. 158, pp. 81–91, 2018.

[223] H. Lai, N. F. Harun, D. Tucker, and T. A. Adams, "Design and ecotechnoeconomic analyses of SOFC/GT hybrid systems accounting for long-termdegradation effects," *International Journal of Hydrogen Energy*, vol. 46, pp. 5612–5629, 2021.

[224] H. Marzooghi and M. Raoofat, "Improving the performance of proton exchange membrane and solid oxide fuel cells under voltage flicker using Fuzzy-PI controller," *International Journal of Hydrogen Energy*, vol. 37, pp. 7796–7806, 2012.

[225] J. Peng, J. Huang, X. L. Wu, Y. W. Xu, H. Chen, and X. Li, "Solid oxide fuel cell (SOFC) performance evaluation, fault diagnosis and health control: a review," *Journal of Power Sources*, vol. 505, article 230058, 2021.

[226] K. W. Eichhorn Colombo, V. V. Kharton, F. Berto, and N. Paltrinieri, "Transient system-level performance and thermo-mechanical stress analysis of a solid oxide fuel cell-based power generation plant with a multiphysics approach," *Computers & Chemical Engineering*, vol. 140, article 106972, 2020.

[227] M. Fardadi, D. F. McLarty, and F. Jabbari, "Investigation of thermal control for different SOFC flow geometries," *Applied Energy*, vol. 178, pp. 43–55, 2016.

[228] G. D'Andrea, M. Gandiglio, A. Lanzini, and M. Santarelli, "Dynamic model with experimental validation of a biogas-fed SOFC plant," *Energy Conversion and Management*, vol. 135, pp. 21–34, 2017.

[229] X. Wu and D. Gao, "Fault tolerance control of SOFC systems based on nonlinear model predictive control," *International Journal of Hydrogen Energy*, vol. 42, pp. 2288–2308, 2017.

[230] Z. Wang, H. Chen, R. Xia, F. Han, Y. Ji, and W. Cai, "Energy, exergy and economy (3E) investigation of a SOFC-GT-ORC waste heat recovery system for green power ships," *Thermal Science and Engineering Progress*, vol. 32, article 101342, 2022.

[231] E. D. Wachsman and K. T. Lee, "Lowering the temperature of solid oxide fuel cells," *Science*, vol. 334, pp. 935–939, 2011.

[232] R. Scataglini, A. Mayyas, M. Wei et al., *A Total Cost of Ownership Model for Solid Oxide Fuel Cells in Combined Heat and Power and Power-Only Applications. Technical Report September*, Environmental Energy Technologies Division, 2015.

[233] T. H. Fleisch, A. Basu, and R. A. Sills, "Introduction and advancement of a new clean global fuel: The status of DME developments in China and beyond," *Journal of Natural Gas Science and Engineering*, vol. 9, pp. 94–107, 2012.

[234] Food and Agriculture Organization of the United Nations, *World Fertilizer Trends and Outlook to 2022. Technical Report*, Food and Agriculture Organization of the United Nations, 2019.

[235] IEA, "The future of hydrogen. Technical Report," IEA, 2019.

[236] IEA, *World Energy Outlook 2020. Technical Report*, IEA, 2020.

[237] IEA, *Oil 2021 - analysis and forecast to 2026. Technical Report*, 2021, https://webstore.iea.org/download/direct/4329.

[238] Methanol Institute, *Methanol Safe Handling Manual -Technical Report*, Methanol Institute, 5th ed edition, 2020.

[239] B. Prabowo, M. Yan, M. Syamsiro, R. H. Setyobudi, and M. K. Biddinika, "State of the art of global dimethyl ether production and it's potentional application in Indonesia,"

Proceedings of the Pakistan Academy of Sciences: Part B, vol. 54, pp. 29–39, 2017.

[240] MARIN, *Sustainable Power Database*, 2021, https://sustainablepower.application.marin.nl/table.

[241] Neste, *Renewable Diesel Handbook. Technical Report*, Neste, 2020.

[242] M. Al-Breiki and Y. Bicer, "Comparative cost assessment of sustainable energy carriers produced from natural gas accounting for boil-off gas and social cost of carbon," *Energy Reports*, vol. 6, pp. 1897–1909, 2020.

[243] A. Al-Enazi, E. C. Okonkwo, Y. Bicer, and T. Al-Ansari, "A review of cleaner alternative fuels for maritime transportation," *Energy Reports*, vol. 7, pp. 1962–1985, 2021.

[244] A. D. Korberg, S. Brynolf, M. Grahn, and I. R. Skov, "Techno-economic assessment of advanced fuels and propulsion systems in future fossilfree ships," *Renewable and Sustainable Energy Reviews*, vol. 142, article 110861, 2021.

[245] Ship & Bunker, *World Bunker Prices*, Ship & Bunker, 2022, https://shipandbunker.com/prices.

[246] TNO, *Power-2-Fuel Cost Analysis. Technical Report*, 2020, https://smartport.nl/.

[247] US Geological Survey, *Nitrogen (Fixed) – Ammonia. Technical Report*, 2021.

[248] H. Derking, L. Van Der Togt, M. Keezer, and C. Bv, *Liquid Hydrogen Storage: Status and Future Perspectives*, Cryogenic Heat and Mass Transfer, 2019.

[249] K. Law, J. Rosenfeld, V. Han, M. Chan, H. Chiang, and J. Leonard, "U.S. Department of Energy Hydrogen Storage Cost Analysis. U.S. Department of Energy," 2013, https://www.osti.gov/scitech/servlets/purl/1082754.

[250] A. Yang, C. Antrassian, and J. Kurtzman, *Production of Dimethyl Ether (DME) for Transportation Fuel Part of the Biochemical and Biomolecular Engineering Commons. Technical Report*, 2020, https://repository.upenn.edu/cbe_sdr.

[251] S. Wang and T. Notteboom, "The Adoption of liquefied natural gas as a ship fuel: a systematic review of perspectives and challenges," *Transport Reviews*, vol. 34, pp. 749–774, 2014.

[252] C. Bourne, T. Nietsch, D. Griffiths, and J. Morley, *Application of Fuel Cells in Surface Ships. Technical Report*, Crown, 2001.

[253] K. Leites, A. Bauschulte, M. Dragon, S. Krummrich, and P. Nehter, "Design of different diesel based fuel cell systems for seagoing vessels and their evaluation," *ECS Transactions*, vol. 42, pp. 49–58, 2012.

[254] J. J. De-Troya, C. Álvarez, C. Fernández-Garrido, and L. Carral, "Analysing the possibilities of using fuel cells in ships," *International Journal of Hydrogen Energy*, vol. 41, no. 4, pp. 2853–2866, 2016.

[255] C. Dall'Armi, D. Micheli, and R. Taccani, "Comparison of different plant layouts and fuel storage solutions for fuel cells utilization on a small ferry," *International Journal of Hydrogen Energy*, vol. 46, pp. 13878–13897, 2021.

[256] W. Li, C. Liu, Y. Hu, S. Yu, B. L. Lv, and Y. Guo, "Diagnosis for timing gearsNoise of a diesel generating set," in *Proceedings of the 13th International Conference on Damage Assessment of Structures: DAMAS 2019*, pp. 582–593, Porto, Portugal, 2020.

[257] L. van Biert, K. Mrozewski, and P. Hart, *Public Final Report: Inventory of the Application of Fuel Cells in the Maritime Sector*, Technical Report, Maritime Knowledge Centre, 2021.

[258] ShipFC, *Green Ammonia Energy System*, ShipFC, 2022, https://shipfc.eu/.

[259] Atena, *FuelSOME*, 2022, https://www.atenaweb.com/en/fuelsome/.

[260] Adaptive Energy, *Endurance Series*, Adaptive Energy, 2022.

[261] S. J. Mcphail, J. Kiviaho, and B. Conti, *Status of SOFC Deployment 2017. Technical Report*, IEA, 2017.

[262] F. Moradi, *AVL Fuel Cell. Technical Report*, AVL, 2016.

[263] BOSCH, *The Stationary Fuel Cell System by Bosch. Technical Report*, 2022, http://www.bosch.com/stories/sofc-system/.

[264] Bloom Energy, "Energy Server 5 Product Datasheet," 2019, https://www.bloomenergy.com/wp-content/uploads/es5-300kw-datasheet-2022.pdf.

[265] Convion, *Products*, 2022, http://convion.fi/products/.

[266] G. D. Blake, "Solid Oxide Fuel Cell Development for Transportation and Stationary Applications:. Technical Report. Delphi. Bloom Energy, 2019," *Energy Server 5 Product Datasheet. Technical Report*, 2010, http://www.bloomenergy.com.

[267] R. Leah, A. Bone, P. Hjalmarsson et al., "Commercialization of Ceres SteelCell ® Technology for power generation and electrolysis," in *15th European SOFC & SOE Forum*, pp. 39–48, Lucerne, Switzerland, 2022.

[268] Doosan, *PureCell Model 400*, 2022, https://www.doosanfuelcell.com/en/prod/prod-0103/.

[269] Fuel Cell Energy, *SureSource 4000. Technical Report*, 2022.

[270] h2e POWER, *Solid Oxide Fuel Cell*, 2022, https://www.h2epower.net/solid-oxide-fuel-cell/.

[271] Power Mitsubishi, *MEGAMIE. Technical Report*, Power Mitsubishi, 2022.

[272] Miura, *Fuel cell FC-5B*, 2022, https://www.miuraz.co.jp/product/thermoelectric/sofc.html.

[273] Osaka Gas Co, *Osaka Gas to Release a New Product. Technical Report*, Osaka Gas Co, 2020.

[274] A. G. Hexis, *Galileo. Technical Report*, Wintherthur, 2017.

[275] Upstart Power, *Products*, 2022, https://www.upstartpower.com/products/#upgennxg.

[276] WATT, *Imperium*, WATT Imperium, 2022, https://www.wattfuelcell.com/portablepower/watt-imperium/.

[277] IMO, *Nitrogen Oxides (NOx) – Regulation 13*, 2020, http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Nitrogen-oxides-(NOx)-\T1\textendash-Regulation-13.aspx.

[278] IMO, *Sulphur Oxides (SOx) – Regulation 14*, 2020, http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Sulphur-oxides-(SOx)-\T1\textendash-Regulation-14.aspx.

[279] O. Schuller, S. Kupferschmid, J. Hengstler, and S. Whitehouse, *2nd Life Cycle GHG Emission Study on the Use of LNG as Marine Fuel. Technical Report*, Sphera, 2021.

[280] D. Stapersma, *Diesel Engines Volume 4, Emissions and Heat transfer. volume 4*, Delft University of Technology, 2010.