Potential of COmbined drive of Fuel cell And Internal Combustion Engine (COFAICE) for naval ships

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Synopsis

Naval vessels around the world are looking to reduce their fuel consumption to not only drive down their environmental impact, but also gain the additional benefit of improving their endurance and reducing their (strategic) dependency on their primary fuel sources. Therefore, based on the strategic value of fuel in the operational environment, multiple navies around the world are investigating alternative energy conversion devices and fuels.

In recent years, solid oxide fuel cells (SOFCs) have gathered increasing attention for maritime applications as an alternative to the traditional diesel engines. SOFCs showcase high power generation efficiency, ultra-low emissions and noise-free operation, which are ideal pre-requisites for power generation onboard naval and commercial ships. Capitalizing on these attributes of SOFCs, this paper aims to investigate the potential of a novel COmbined drive of Fuel cell And Internal Combustion Engine (COFAICE) for naval vessels that employs a SOFC-ICE integration concept for power generation.

In this paper, the performance of SOFC-ICE integration is tested for three different case studies of naval ships, namely, an oceangoing patrol vessel, a landing platform dock and a high-speed surface combatant. We investigate the optimal load sharing between the two energy conversion devices for different operational profiles and operating modes of a notional naval vessel. Optimal load sharing strategies are generated to study the impact on power-generation efficiency and CO_2 emissions while taking into account the space and weight considerations for the system and fuel bunkering. The performance of the natural gas-fuelled SOFC-ICE integration concept is compared against the conventional and existing power plants onboard comparable ships. Furthermore, based on the optimal power split, potential of two SOFC-ICE integration methods are investigated for part-load operations. We find that significant improvements in efficiency and CO_2 emission reductions can be achieved for the integrated SOFC-ICE power plants with optimized space and weight considerations.

Keywords: Solid oxide fuel cell; Marine natural gas engine; COFAICE; System integration; Naval ships; Optimal load sharing

1 Introduction

Over the past few decades, the International Maritime Organization (IMO) has been putting regulations in place to actively reduce the emissions caused by ships. The regulations cover allowable limits for NO_x and SO_x emissions [1], the definition of the Energy Efficiency Design Index (EEDI) [2] for new ships, and the Ship Energy Efficiency Management Plan (SEEMP) for all ships. Naval vessels, which have the theoretical possibility to exempt themselves from these regulations, are also looking to reduce their fuel consumption. With this naval initiative, the aim is to not only drive down their environmental impact, but also gain the additional benefit of improving their endurance and reducing their (strategic) dependency on their primary fuel sources. The Operational Energy Strategy (OES) published by the Royal Netherland Navy [3] supports these claims by stating that the (restricted) availability of fossil fuel will limit the operational freedom of commanders in the field. Parallel to this, the need to operate within the Emission Control Areas (ECAs), being able to police within these zones and being able to enter ports within these zones to resupply, may be considered as important motivations to adhere to the latest regulations.

Authors' Biographies

Ir. Harsh Sapra is a PhD researcher at Delft University of Technology working on the performance integration of a solid oxide fuel cell and an internal combustion engine along with underwater exhaust system. His research is focussed towards experimental and simulation-based investigations of marine engine performance on alternative fuels.

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With the advent of these new emission abatement measures, comes a large influx of technical solutions to bring onboard in order to meet the regulations - e.g. exhaust after-treatment systems [4], new combustion engine technology [5] and new fuel types [6]. Many of these solutions have a significant impact on naval ship design because of the reduction in energy and/or power density. The current fuel of choice, NATO-standard F76, has an excellent (stored) energy density when compared to newer more sustainable fuels [7, 8], making it difficult to carry the same energy without increasing the storage volume and weight, thus, impacting the ship design. A remedy is to convert the fuel more efficiently to power, reclaiming the losses from the less-energy-dense fuel. A more efficient conversion of fuel can be obtained by choosing an engine with better thermal efficiency, e.g. a low(er) speed diesel engine or choosing a completely different energy conversion device like a fuel cell. The main drawback is that for both these solutions, a power density penalty is incurred when comparing the systems to high-speed diesel engines or even gas turbines that are typically used for the higher speed surface combatants. By accepting a reduction in power density it becomes necessary to modify the ship design to create more space, by either sacrificing space used for other ship functions or by reducing the bunker space, directly affecting the energy carried and thus the endurance of the vessel. As a consequence, by having a relatively small bandwidth in the power and energy density, the emission abatement measures that can be easily implemented into a naval ship design are scarce.

With the set of regulations that are currently in place, the more stringent limits for NO_x (tier III) can be met by installing exhaust gas after-treatments on diesel engines, and by gas turbines without any after-treatment [9, 10]. Thus, from the standpoint of meeting the current regulations, the motivation for other emission abatement measures may be weak for naval applications. However, it does not take away the earlier arguments regarding the strategic value of fuel in the operational environment. Multiple navies around the world are investigating alternative fuels and energy conversion devices. For instance, navies are experimenting with bio-diesel as a 'drop-in' alternative or additive to regular fossil-based diesel [11] and, by doing so, reducing their immediate reliance on fossil resources. Additionally, utilizing the fuel more efficiently will remain of great importance. Therefore, it is useful to not only consider alternative fuels but to also consider the energy conversion efficiency.

While the traditional diesel generators are thermomechanical devices, a fuel cell is an electrochemical energy conversion device, which directly generates electricity and heat from a gaseous or gasified fuel via an electrochemical reaction between the fuel and oxidant. Depending on the chemistry of the fuel cell (FC) and the fuel, additional efficiency improvements of 10-15% are possible compared to a reciprocating internal combustion engine. Additionally, FCs emit ultra-low emissions and allow for noise-free operation, which are promising attributes for maritime (naval) applications [12]. The integration of standalone fuel cells in ship power generation systems has been studied by [12], [13] and [14]. In these studies, a number of different fuel cell chemistries are used with power outputs varying between a few dozen kilowatts to several hundred kilowatts. These studies indicate the increasing interest of the maritime industry in fuel cell systems for onboard power generation. Therefore, a solution for naval vessels could come from a hybrid combination of systems.

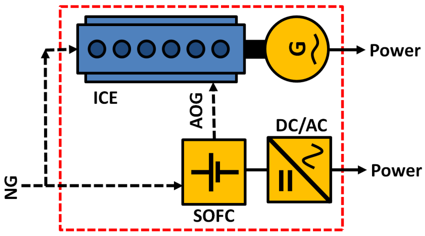

Figure 1: Outline of the GasDrive (COFAICE) power generation concept. DC/AC: DC to AC converter, G: Generator

Motivated by the promise of higher efficiency and ultra-low emissions, this paper investigates the applications of a novel, hybrid power generation system designated as COFAICE or COmbined drive of Fuel cell And Internal Combustion Engine for naval vessels. The COFAICE system proposes a serial integration of a solid oxide fuel cell (SOFC) with a marine natural gas internal combustion engine (ICE) to meet the onboard power requirements. Figure 1 shows the outline of the GasDrive (COFAICE) power generation concept, consisting of a SOFC and an integrated ICE. In GasDrive, the SOFC delivers high-efficiency electrical power, and the anode-off gas (gas at the fuel cell exhaust) is blended with NG and combusted in an ICE to produce the remaining power. The SOFC anode-off gas (AOG) is a mixture of hydrogen, carbon monoxide, carbon dioxide and water vapour. The water is condensed out, leaving behind a high-quality blend of hydrogen, carbon monoxide and carbon dioxide. Thus, the AOG contains combustible energy in the form of high percentages hydrogen and carbon monoxide, which can be combusted in a marine natural gas engine for additional power generation, thus, leading to enhanced system efficiency and significant reductions of NOx, SOx, PM, unburnt hydrocarbons and CO_2 emissions through integration [8]. Although the research presented in this paper is on natural gas-fuelled SOFC-ICE systems, methanol and ammonia are also considered as potential fuels for SOFC-ICE integration.

In this paper, three case studies of naval ships are outfitted with the GasDrive (COFAICE) system to investigate the impact of SOFC-ICE integration on marine power generation for naval applications. The case study will provide key figures regarding the system efficiency in a number of operating points, demonstrating part-load behaviour of SOFC-ICE system Furthermore, the paper will provide crude estimations of how the space and volume requirements are affected by contrasting the weight and dimensions of the hypothetical GasDrive system with the current traditional layout for each of the vessels. The paper also discusses the potential reductions in CO_2 emissions for the natural gas-fuelled SOFC-ICE system employed for naval applications. Lastly, the paper concludes with a discussion on the unexplored potential of SOFC-ICE integration for maritime applications.

The next section covers the methodology adopted for this research and describes the three case studies with their corresponding operational data.

2 Methodology

In this paper, three case studies of naval ships are analysed to study the impact of SOFC-ICE integration. The 3 case studies include an oceangoing patrol vessel (OPV), a landing platform dock (LPD) and a high-end surface combatant (HSC). In this section, the current system configuration and typical operational data for each of these naval vessels is described. The current configurations are replaced by the GasDrive (COFAICE) system based on optimal load sharing. The calculations for optimal load sharing are described in the last subsection. Based on the optimal load sharing, the impact of SOFC-ICE integration on power-generation efficiency, emissions and space and weight considerations for engine room and bunkering are studied for the three case studies.

2.1 Case study 1: Oceangoing patrol vessel (OPV)

The OPV analysed in this paper originally has a hybrid architecture as shown in Figure 2(a). Three high-speed diesel generators of 0.9 MWe each are installed to generate electrical power requirements while two high-speed diesel engines of 5.4 MW each are used for propulsions. The propulsion load can be met by the high-speed diesel engines or diesel generators, however, the hotel load solely interacts with the diesel generators. Therefore, the two high-speed induction electric motors of 0.4 MWe each allow for only power take-in (PTI) configuration and not power take-off (PTO). Overall, the system operates in CODLOD configuration, i.e. combined diesel-electric or diesel engine. The current system operates on NATO-specifications diesel fuel, i.e. F76. The ship is considered to have a current bunkered fuel capacity of 500 m^3.

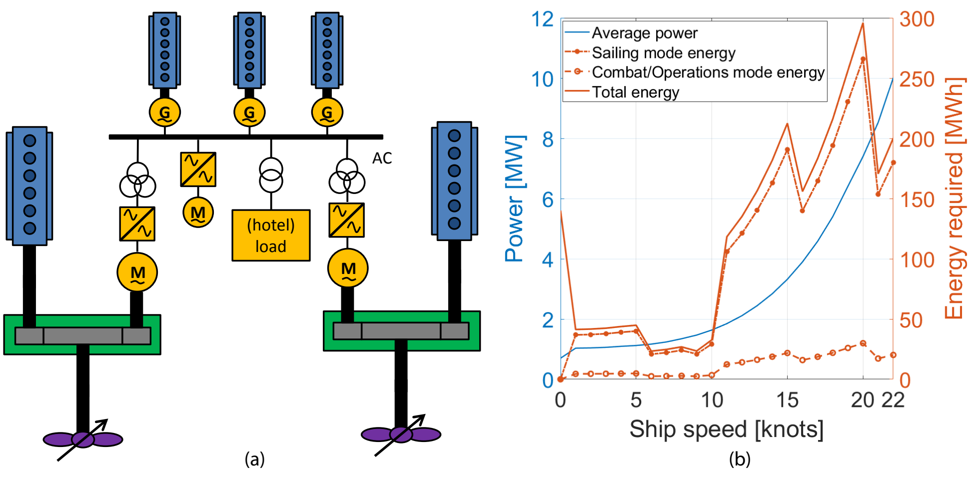

Figure 2: Current system configuration (a) and data including average power and energy requirements for different operational modes (b): Case study 1

Table 1: Hotel load requirements and division of operational time for each of the three modes: Case study 1

Mode	Harbour/Anchor	Sailing	Combat/Operations
Power [MWe]	0.7	1	1.1
Time [%]	20	72	8

The hotel load requirements and division of operational time for each of the three modes are given in Table 1. All three cases studies are considered to have a total operational time of 1000 hours. Figure 2(b) shows the onboard

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energy requirements of the ship for sailing and combat mode at different ship speeds. The total energy requirement also includes harbour load of the OPV, which is 140 MWh at anchor (0 knots) as shown in Figure 2(b). Based on the total energy requirements at each ship speed, the average onboard power requirement is calculated and plotted in Figure 2(b).

2.2 *Case study 2: Landing platform dock (LPD)*

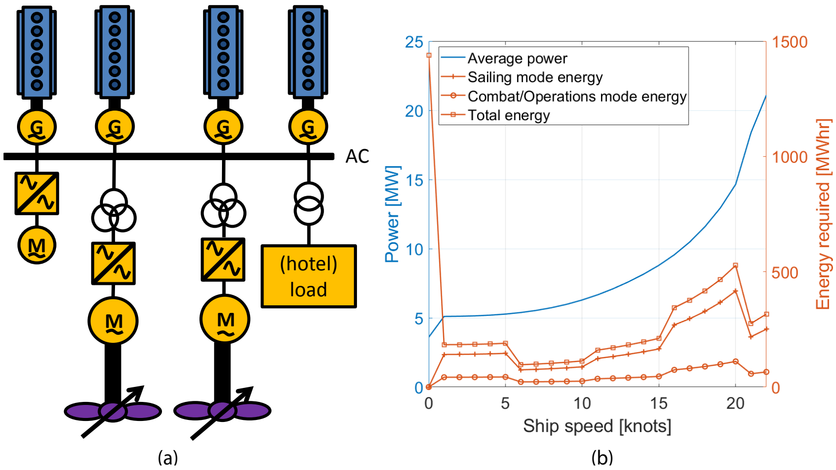

Figure 3: Current system configuration (a) and data including average power and energy requirements for different operational modes (b): Case study 2

The LPD has a full electric propulsion system as shown in Figure 3(a). Four low-speed diesel generators of 5.5 MWe each are installed to generate the onboard power requirements including hotel and propulsion power. The propulsion power is delivered to two induction motors with a rated power of 9 MWe each. The current system operates on NATO-specifications diesel fuel, i.e. F76. The LPD is has a total fuel bunkering capacity 7700 m^3. Out of which, 1500 m^3 of fuel is used for its own onboard power requirements including propulsion.

In case of the LPD, the hotel power requirements and division of operational time for each of the three modes are given in Table 1. Figure 2(b) shows the onboard energy requirements of the ship for sailing and combat/operations mode at different ship speeds. The total energy requirement also includes harbour load of the LPD, which is 1440 MWh at anchor (0 knots). Based on the total energy requirements at each ship speed, the average onboard power requirement is calculated and plotted in Figure 3(b).

Table 2: Hotel load requirements and division of operational time for each of the three modes: Case study 2

Mode	Harbour/Anchor	Sailing	Combat/Operations
Power [MWe]	3.6	4.9	5.9
Time [%]	40	48	12

2.3 *Case study 3: High-end surface combatant (HSC)*

Onboard a typical HSC, the current topology is divided between power generation for hotel load requirements and shaft propulsion as shown in Figure 4(a). The current system consists of four 1 MWe high-speed diesel generators for electrical power generation. The current system also operates two high-speed diesel of 4 MW each and one gas turbine of 30 MW to generate propulsion power. The current system operates on NATO-specifications diesel fuel, i.e. F76. The ship is considered to have a current fuel capacity of 700 m^3.

Table 3: Hotel load requirements and division of operational time for each of the three modes: Case study 3

Mode	Harbour/Anchor	Sailing	Combat/Operations
Power [MWe]	1.1	1.4	1.9
Time [%]	40	48	12

The propulsion power is generated by diesel engines, gas turbines or a combination of the two. The hotel power requirements and division of operational time for each of the three modes are given in Table 3. Figure 4(b)

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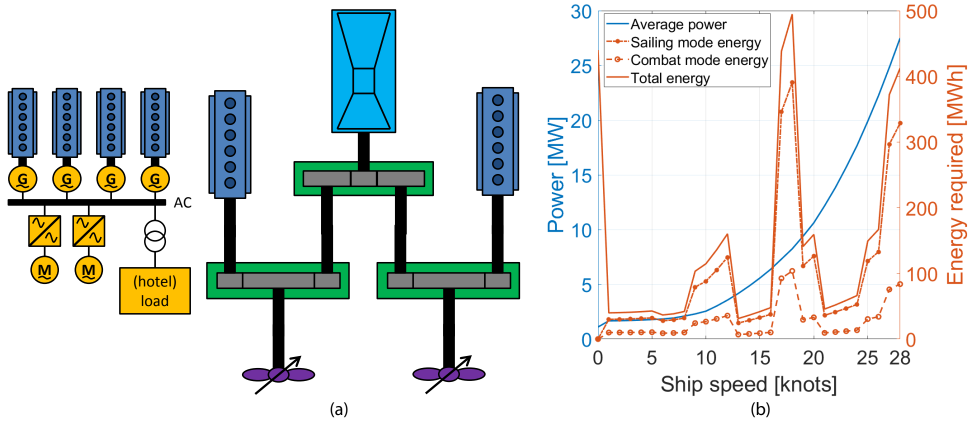

Figure 4: Current system configuration (a) and data including average power and energy requirements for different operational modes (b): Case study 3

shows the onboard energy requirements of the ship for sailing and combat mode at different ship speeds. The total energy requirement also includes harbour load, which is 440 MW h at anchor (0 knots). Based on the total energy requirements at each ship speed, the average onboard power requirement is calculated and plotted in Figure 4(b). The system is considered to operate on the high-speed diesel engines till 19 knots beyond which the gas turbines are switched on.

The above described operational data for each case study is used to calculate the optimal load sharing at rated conditions for SOFC-ICE integration as described in the next subsection.

2.4 Calculation Method

This subsection details the generic calculation method applied to each case study to determine the optimal load SOFC-ICE power split. The subsection also describes the efficiency, CO_2 emissions and space and weight calculations.

The average power (P_{avg}) shown in Figures 2 to 4 for the three case studies is determined from the total energy (E_{avg}) requirement of the ship and the operational time spent (t) at each speed point (i), as given by eq. (1).

$$P_{avg_i} = \frac{E_{avg_i}}{t_i} \tag{1}$$

With the required energy and power known at each speed (v) point, the next step is to determine the accumulated energy (E_{acc}) at each speed (from 0 to maximum speed) with eq. (2). Next, accumulated energy percentages are calculated by dividing the accumulated energy at each speed by the total accumulated energy at maximum ship speed. Parallel to accumulated energy percentage, average power percentages are also calculated at each ship speed.

$$E_{acc_i} = \sum_{i=0}^{v_{max}} E_{avg_i} \tag{2}$$

In order to find the optimal power split between the SOFC and the ICE, the corresponding average power percentage at every ship speed is assumed to be generated by the SOFC while the remaining power is generated by the ICE. For example, if the average power percentage for a case study at a low ship speed corresponds to 18 %, then the SOFC-ICE power split is 18-82. As the ship speed increases to the maximum value, the SOFC power percentage increases to 100 % for each case study, indicating that all the onboard power is generated by the SOFC. For each case, the data of accumulated energy against SOFC power percentage is plotted in the results section. When selecting a SOFC power fraction, this curve shows how much of the total onboard required energy can be generated with SOFC power. After calculating the different power splits, the impact of changing SOFC-ICE power splits on efficiency, space and weight can be estimated for rated conditions.

Selecting a power split between SOFC and ICE results in an energy split, which is used to determine the total SOFC-ICE system ($\eta_{SOFC-ICE}$) efficiency, given by eq. (3).

$$\eta_{SOFC-ICE} = \frac{1}{\frac{E_{SOFC}[\%]}{\eta_{SOFC}} + \frac{E_{ICE}[\%]}{\eta_{ICE}}} \tag{3}$$

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where $E_{SOFC}[\%]$ is the onboard energy percentage met by the SOFC at the corresponding power split, which is equal to corresponding accumulated energy percentage. $E_{ICE}[\%]$ is the remaining energy percentage, which is equal to $E_{SOFC}[\%]$ subtracted from the 100 % onboard energy requirement.

An average efficiency is used for each component, based on values from the literature. The power split determines the total mass and volume of the SOFC and ICE. η_{SOFC} is the SOFC efficiency, which is taken to be equal to 65 % [LHV, AC] based on the data available for the state-of-the-art Bloom Energy Server (ES5-300kW) [15]. η_{ICE} is the integrated engine efficiency, which based on the efficiency of the CAT CG170-20 natural gas engine [16]. However, for the GasDrive system, the engine efficiency is not directly equal to 44 %, but improves due to blending of SOFC anode-off gas and natural gas as explained in the following paragraph.

To calculate the system efficiency for SOFC-ICE integration based on the GasDrive concept, the impact of SOFC anode-off gas components on the efficiency of the integrated NG engine needs to be taken into account. In a recent paper, the authors employed experimental and simulation-based investigations to study SOFC-ICE integration [8]. In this recent paper, the authors found that by blending 30 % (by volume) SOFC anode-off gas (AOG) with 70 % natural gas (NG), the efficiency of the integrated engine can be improved by 2 to 3.5 % depending on SOFC-ICE power split and fuel utilization compared to a conventional marine engine operating on 100 % natural gas. The efficiency improvement is attained through a combination of improved combustion and replacement of natural gas fuel by hydrogen coming from the SOFC. Next to engine efficiency, the efficiency of the integrated system was found to be higher by 5 to 8 % compared to a conventional marine NG engine of same power output. For the analysis performed in the current paper, it is considered that at 25-75 SOFC-ICE power split, the SOFC produces just enough anode-off gas to operate the engine with 30-70 AOG-NG blend percentage. This means that for SOFC load shares below 25 %, the anode-off gas flow rate required by the integrated engine to maintain a 30-70 AOG-NG blend and the corresponding efficiency improvements may not be available from the SOFC. Thus, it is assumed that the integrated engine is operated with a 30-70 AOG-NG blend for SOFC-ICE power splits higher than 25-75, which provides an efficiency improvement of 2 % over the conventional marine NG engine as the SOFC is operated at 80 % fuel utilization. Therefore, in eq. 3, η_{ICE} is taken to be 2 % higher than the original efficiency of 44 % for power splits higher than 25-75. In this manner, the system efficiency is calculated for different power SOFC-ICE power splits.

Next, the system space and weight requirements are computed. The power split determines the total weight and volume of the SOFC-ICE system. Based on the power delivered by each component and assumed power densities, the size and weight of the GasDrive system is computed for each power split. The volumetric and gravimetric power densities of the SOFC and the ICE have been provided in Table A.1. To calculate the fuel bunkering space and weight requirements for the GasDrive system based on the power splits, the following procedure is followed. First, the current bunkered energy of the ship is calculated based on the current system configuration described for each case study. The bunkered energy is calculated by multiplying the current fuel bunkering capacity [m^3] by the volumetric energy density of F76 (39.54 $\mathrm{MJ\,L^{-1}}$). From this bunkered energy, only a certain amount of energy is useful for onboard power generation due to the efficiency of the existing ship engines. This useful energy onboard the ship is computed by multiplying the bunkered energy with the weighted average of the efficiencies of the installed engines. In this paper, typical specific fuel consumption values are assumed for the diesel generator sets and the high-speed diesel engines for each case study, which are representative values for typical engines employed for naval applications. The assumed specific fuel consumption data for the engines corresponding to each case study has been provided in Appendix A.

After calculating the useful energy onboard the ships, the new bunkered energy ($E_{Bunker,SOFC-ICE}$) [MJ] requirement corresponding to the SOFC-ICE system is estimated by dividing the useful energy by the new SOFC-ICE system efficiency. Based on the new bunkered energy for each power split, new bunkering volume [m^3] and weight [tonnes] can be calculated from eq. 4 and 5, respectively. The total volume and weight corresponding to the SOFC-ICE system and the current architecture is the sum of the bunker specifications and the system specifications with respect to the computed space and mass values. In this paper, these space and weight considerations for the GasDrive system calculated for each case study are compared against those estimated for the current system onboard the ships.

$$\mathrm{Volume}_{Bunker,SOFC-ICE} = \frac{E_{Bunker,SOFC-ICE}}{E.D._{Vol.,LNG} * 3600} \tag{4}$$

$$\mathrm{Weight}_{Bunker,SOFC-ICE} = \frac{E_{Bunker,SOFC-ICE}}{E.D._{Grav.,LNG} * 3600} \tag{5}$$

where $E.D._{Vol.,LNG}$ is the volumetric energy density of LNG (including storage), which is taken to be equal to 3.3 $\mathrm{kWh\,L^{-1}}$. Similarly, $E.D._{Grav.,LNG}$ is the gravimetric energy density of LNG (including storage), which is taken to be equal to 7.4 $\mathrm{kWh\,kg^{-1}}$ [12].

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To calculate the volume and weight of the current system, a gravimetric and volumetric power density for the diesel generators sets and high-speed diesel engines are assumed. These values have been provided in Table A.1 of Appendix A, and are representative values for typical diesel generator sets and engines employed for naval applications. Additionally, the current bunkering volume and weight values are estimated from the current bunkered energy and energy densities of diesel fuel. The assumed volumetric and gravimetric densities for diesel (including storage) are $8.2\,\mathrm{kWh\,L^{-1}}$ and $8.3\,\mathrm{kWh\,L^{-1}}$[12].

Besides efficiency and system size calculations, CO_2 emissions in [$\mathrm{g\,kW^{-1}\,h}$] are also calculated in this paper for the current and SOFC-ICE system. The CO_2 emissions are estimated from specific fuel consumption (sfc) based on the assumption of complete conversion of carbon in consumed fuel to CO_2.

3 Results

3.1 Case Study 1: OPV

Figure 5(a) shows the accumulated energy against SOFC power percentage for the oceangoing patrol vessel case. With 100 % of installed power, 100 % of the total energy requirement can be met by the SOFC. This curve also shows that with 80 % of SOFC power, only 85 % of the total energy requirement can be generated. By varying the installed SOFC power, the energy split results in a total system efficiency, as explained in the methodology section. This system efficiency as a function of the percentage of SOFC power is also shown in Figure 5(a). Highest system efficiency can be achieved when all of the onboard electric energy is produced with the SOFC, and this will, therefore, also result in the lowest emissions from the ship. A higher efficiency means that less fuel is needed for the same operation. The decrease in required LNG fuel volume (including storage) as a function of SOFC power is shown in Figure 5(b). This figure shows that the total system volume has a general increasing trend with installed SOFC power due to the lower power density of the SOFC compared to ICE. The trends of bunker volume and system volume lead to a net increase in total volume as the SOFC power fraction increases. The same can be said for the total weight (including bunker and system), which is also shown in Figure 5(b). Therefore, the results for this case study show that selecting a SOFC-ICE power split that favours the SOFC results in a higher efficiency, but increased total volume and weight.

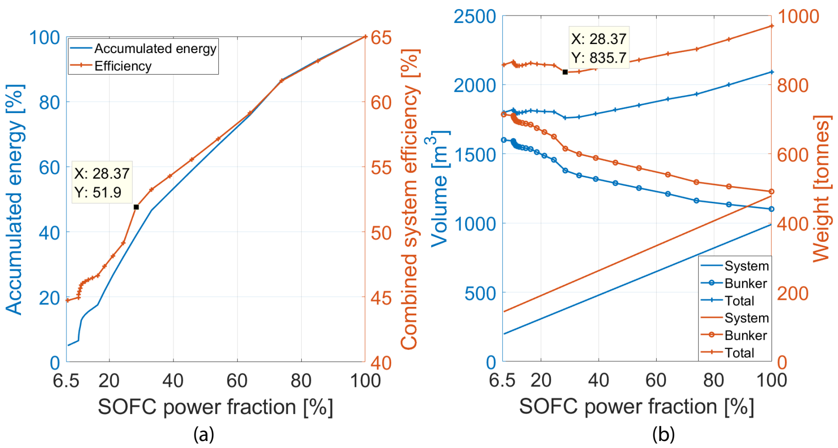

Figure 5: Accumulated energy percentage and SOFC-ICE system efficiency v/s SOFC power percentage (a). System volume and weight vs SOFC power percentage (b): Case study 1

However, the decreasing trend of bunker volume and weight in contrast to the increasing trend of system specifications provides an optimal point that corresponds to the lowest total volume and weight. For the OPV, this optimal value corresponds to about 28 % SOFC load share, which results in a system efficiency of about 52 % based on average power calculations. The resultant efficiency improvement is about 9 % compared to the current system onboard the OPV. At the optimal SOFC-ICE power split (PS) of 28-72, the GasDrive system (including bunkering) is computed to be 2.13 times larger in volume and 1.08 times heavier in weight. Therefore, although the increase in volume may be substantial, the increase in relative weight is not significant. Furthermore, installation of the GasDrive system with a 28-72 PS could lead to potential CO_2 reductions of 41 %.

3.2 Case Study 2:LPD

Figure 6(a) shows the accumulated energy against SOFC power percentage for the LPD. Compared to the OPV, LPD has a higher rate of accumulated energy, thus, 80 % of SOFC power can meet more than 90 % of the total energy requirements. Although the system volume and weight show increase at very high SOFC power fractions,

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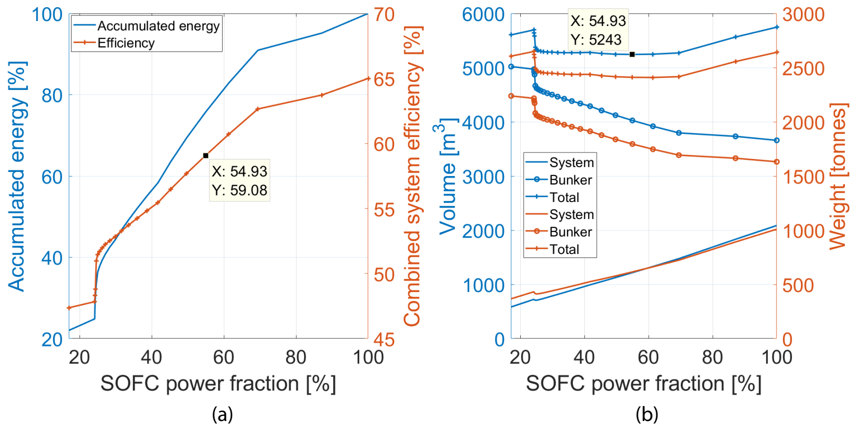

Figure 6: Accumulated energy percentage and SOFC-ICE system efficiency v/s SOFC power percentage (a). System volume and weight vs SOFC power percentage (b): Case study 2

the difference between system specifications at the lowest SOFC load share (17 %) and 100 % load share is not significant. In case of the LPD, there is a drastic decrease in bunker (fuel) specifications due to much higher (minimum) SOFC power fractions contributing to large onboard energy requirements, as seen from Figure 6. Although the total volume and weight variations seem constant for a significant percentage of the SOFC power fractions, an optimal is found close to the SOFC power rating of 55 %.

At the optimal SOFC-ICE PS of 55-45, the GasDrive system efficiency based on average power was computed to be as high as 59 %. This is a significant improvement over the current system, which was estimated to have a system efficiency of 47.63 % based on weighted average efficiency calculations. The efficiency improvement indicates a reduction of CO_2 emissions by about 43 %. However, in case of the LPD, these improvements come with a significant penalty on system specifications. At the optimal PS, the SOFC-ICE system (including fuel bunkering requirements) was about 3.7 times bigger and almost 2 times heavier. Although in this analysis an optimal power split of 55-45 is presented, choosing a higher SOFC load share of 69 % would further increase the efficiency by 4 % with almost insignificant increments in weight and size due to the nearly constant requirements of total weight and volume as seen in Figure 6(b).

In addition to efficiency, size and emissions, two very important factors not considered in this study are cost and redundancy. To keep the cost as low as possible and the redundancy high, the installed SOFC power should probably be a relatively smaller fraction of the total power. Based on the type of vessel (and, thus, operating profile), a small fraction of SOFC power might still have a considerable impact on the total system efficiency.

3.3 Case Study 3: HSC

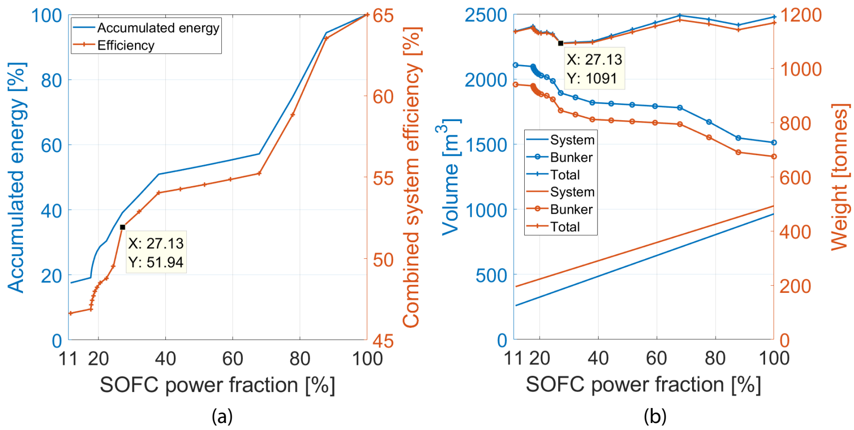

Figure 7: Accumulated energy percentage and SOFC-ICE system efficiency v/s SOFC power percentage (a). System volume and weight vs SOFC power percentage (b): Case study 3

Unlike the OPV and LPD case studies, in case of the HSC, the GasDrive system was analysed to replace only the diesel generators and the higher speed diesel engines and, thus, not the entire current architecture. This was done to retain the very high speed (20-28 knots) operation functionality of the gas turbines for the HSC. Therefore,

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in this case study, the 100 % energy and power ratings analysed for this case study correspond to the hybrid system architecture of diesel generators (DGs) and high-speed diesel (HSD) engines excluding the gas turbines. Therefore, the current hybrid system consisting of DG and HSD engines is replaced by an electrical architecture powered by a SOFC and ICE. Since the HSD powered mechanical propulsion part of the current architecture is replaced by an electrical system, for this case study, additional space and weight considerations for the induction motors and converters are included in the system size calculations. In this paper, for every additional motor (with output equivalent to the ICEs) a weight of 15 tonnes and space of 10 m^3 is assumed while each frequency converter (FC) is assumed to weigh 7 tonnes and occupy 8 m^3 of space. The details of the GasDrive system employed in the HSC case study will be discussed further in the discussions section.

As seen from Figure 7(a), the increasing trend of accumulated energy percentage has a very different trend for the HSC due to the difference in operational profile. In case of the HSC, a distinct optimum was found at about 27 % of SOFC power fraction, which provided a system efficiency improvement of 9.7 %. This corresponded with 36 % CO_2 reduction. In this case study, these performance improvements can be gained with a weight increment of only 1.06 times and a space (system + bunkering) increment of about 2 times. Thus, significant ship performance improvements could be gained by integrating a smaller load share SOFC with an ICE while leveraging relatively smaller increments in system specifications.

4 Discussions: Part-load operation and unexplored potential of SOFC-ICE integration

The results presented in the previous section are for rated operating conditions, however, for a complete understanding of the impact of SOFC-ICE integration, it is vital to investigate the part load operations as well. Therefore, in this section, the impact of SOFC-ICE integration and its untapped potential are further discussed at part loads for case study 3.

Based on the optimal power split of 27-73, two GasDrive packs are installed with $SOFC_1$ of 1.4 MWe and $SOFC_2$ of 1.9 MWe while each ICE is of 4.35 MWe, as shown in Figure 8. The SOFCs are matched to provide the constant load demand of hotel load during each mode, thus, providing constant and high-efficiency power generation. The propulsion power (PP) during sailing and combat modes is same and, delivered by the ICEs. As the ship speed increases, the real-time SOFC-ICE PS changes with increasing load demand, as seen in Figure 9(a) and Figure 10(a) for the two modes. For instance, at the lowest speed, the SOFC load share is about 89 %, which decreases to about 26 % at 15 knots in the sailing mode because the SOFC power remains constant (hotel load) while the ICE_1 load share increases. After 15 knots, the total load requirements is beyond the capacity of one GasDrive pack, therefore, the other engine (from the other GasDrive pack) is switched on with equal load sharing between the two engines, also seen in Figure 9(a). In this analysis, the SOFCs are considered to provide the constant hotel load demands due to their limited dynamic capabilities [12, 17]. Therefore, at high speeds, one engine (running on 30-70 AOG-NG blend) is integrated with the SOFC while the other one operates individually on only NG to meet the additional load requirements.

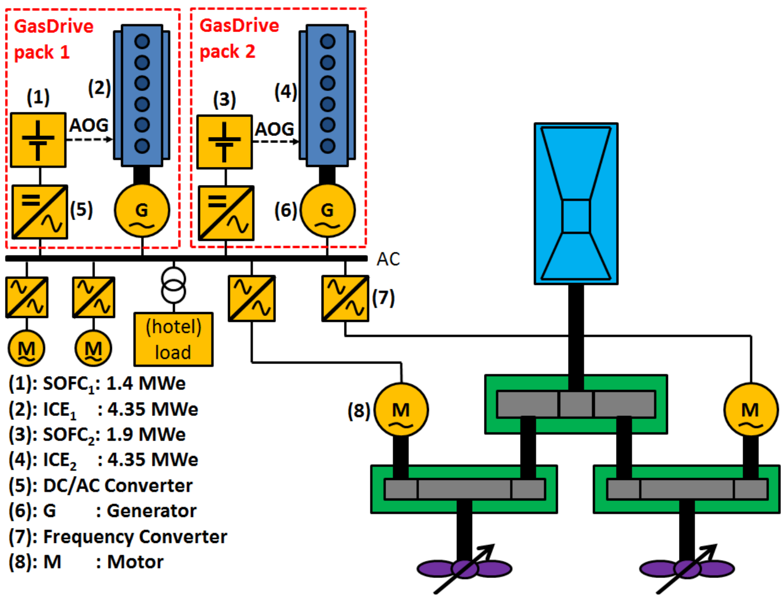

Figure 8: New system configuration with SOFC-ICE integration: Case study 3

Based on the load share of each component, individual efficiencies are calculated at each ship speed. While

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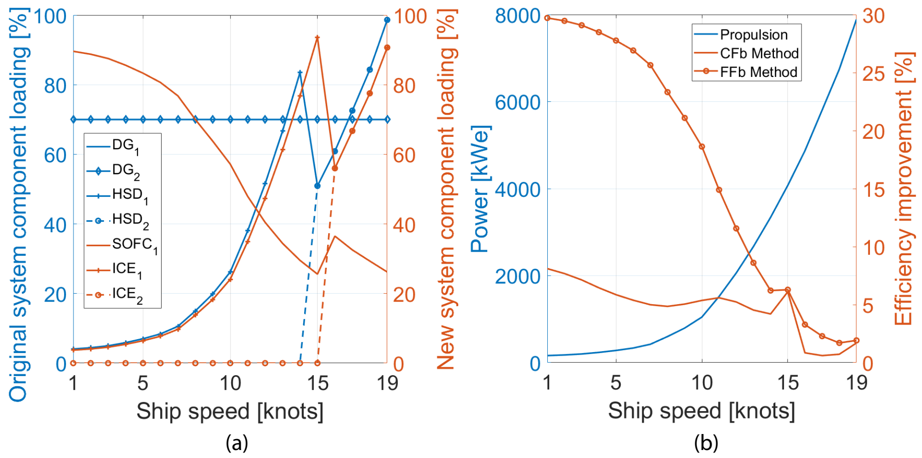

Figure 9: Load sharing between components for the new (SOFC-ICE) and original systems during sailing mode (a). Propulsion power and efficiency improvements based on the two integration methods (b)

the SOFC efficiency is fixed at 65 %, the assumed part load NG engine efficiencies are given in Table A.5. For the engine integrated with the SOFC and operating on the 30-70 AOG-NG blend, an additional 2 % improvement is added over to account for the impact of AOG, as explained in the methodology. Based on loading and efficiency of each component, total system efficiency and CO_2 emissions are computed at each speed for the new SOFC-ICE system. In the efficiency calculations, assumed efficiencies of 97 % for motor and converter, 98 % for gearbox and 99 % for shaft are also taken into account [18] since the mechanical propulsion part is replaced by an electrical architecture.

Until now, the SOFC-ICE integration operates with a constant 30-70 AOG-NG blend inside the engine. For the proceeding discussion, this integration approach is referred to as constant fuel blend (CFb) Method. In this paper, a second method is proposed, which showcases the untapped potential of SOFC-ICE integration. This second method is called as the flexible fuel blend (FFb) method, in which, the SOFC is integrated with a flexible fuel blend (FFb) engine capable of operating on any blend of anode-off gas and natural gas ranging from 100 % AOG to 30-70 AOG-NG to 100 % NG. In this method, up to a certain load, the FFb engine would operate on only AOG to meet the small part load requirements. Beyond that load percentage, the amount of NG blended with AOG would be increased to generate additional power at higher load percentages. Operation on only AOG could lead to even higher system operation efficiency of 70 % at part loads. The efficiency improvement can be attributed to additional power generation by the engine operating on only SOFC AOG. Operation at higher loads would require blending of NG with the AOG to produce the higher power outputs, thus, decreasing the system efficiency below 70 %. However, the efficiencies could still be much higher than a conventional marine NG engine at the same load due to large percentages of anode-off gas in the AOG-NG fuel blend.

In this paper, this unexplored potential of SOFC-ICE integration is also investigated based on certain assumptions, which are as follows. In the FFb method, the integrated FFb engine is assumed to be able to produce 10 % of SOFC-ICE system load operating on only SOFC AOG. Chuahy et al. showed that an optimised SOFC-ICE system with 85-15 PS could reach about 70 % efficiency while the engine operated on only AOG using advanced combustion technology [19]. Beyond the 10 % load share, the efficiency is assumed to linearly decrease as the engine load and the amount of NG blended with AOG increases. In such a case, the SOFC-ICE efficiency would linearly decrease from about 70 % at 10 % load share and only AOG to about 50 % at 75 % engine load share and 30-70 AOG-NG blend. To compute these SOFC-ICE efficiencies, a linear relation is fitted with the FFb engine load share from the SOFC-ICE PS as the input. Using these efficiencies of SOFC-ICE integration approach, the system efficiencies are again calculated till 15 knots for both the modes. Beyond 15 knots, the other ICE is switched on with equal sharing as explained for the CFb method. The efficiency of the other ICE operating on only NG is computed using a polynomial fit of the efficiencies given in Table A.5, as a function of load percentages. With the efficiency and load sharing of SOFC-ICE integration and the other ICE known at each speed, total system efficiency and CO_2 emissions are computed for the FFb method as well and compared against the original system.

As seen in Figure 9(a), in the original system, two DGs share the hotel load equally while the propulsion load is met by the two HSDs. After reaching close to full loading of the first HSD, the second HSD is swicthed on with equal load sharing. Similar to the new system, efficiencies for each component are estimated at each speed based on a polynomial fits with loading percentage as input. Table A.2 and Table A.4 provide the assumed part load efficiencies of the DGs and HSDs, respectively. In this case, losses corresponding to efficiencies of 98 % and 99 % for the gearbox and shaft are taken into account because only the mechanical part from the original system is

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replaced while the remaining electrical components are retained. In this manner, total system efficiency and CO_2 emissions are computed for the original system as well.

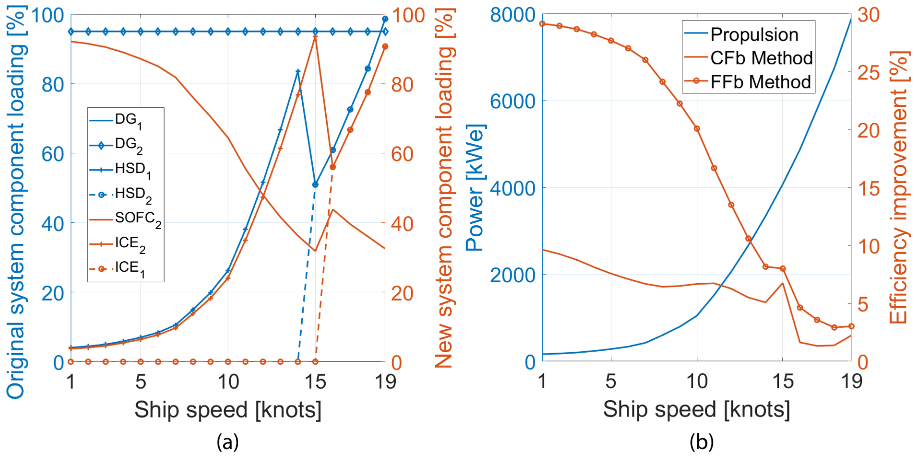

Figure 10: Load sharing between components for the new (SOFC-ICE) and original systems during combat mode (a). Propulsion power and efficiency improvements based on the two integration methods (b)

Figure 9(b) and Figure 10(b) show the same propulsion power needed during sailing and combat mode in addition to the efficiency improvements attained from SOFC-ICE integration via the CFb method and the FFb method compared to the original configuration. CFb method shows a maximum improvement of about 8 % while the FFb method projects an improvement of about 30 % at the lowest speed. The very high-efficiency improvements with the FFb method at low speeds are due to the higher load share of SOFC in addition to the much higher efficiencies of the FFb ICE operating on flexible blends with much higher percentages of AOG than NG. This higher load share of SOFC at low speeds corresponds to the hotel load during the two modes, and remains constant, while the propulsion power requirements at these speeds are relatively lower. In case of the CFb method, although the power split is the same, the efficiency of the engine is much lower due to the constant 30-70 AOG blend and the inherently low efficiency of the ICE at part loads, which leads to lower system efficiency improvements. At higher speeds, the efficiency with FFb method is much higher as the engine is assumed to be operating on a blend of AOG-NG that is higher than 30-70 and favours the AOG. In the FFb method, as the engine speed increases the percentage of NG in the fuel blend increases to meet the additional load, which reduces the efficiency of the engine compared to only AOG, however, it is much higher than the conventional engine.

In both the modes, the potential efficiency improvements due to SOFC-ICE integration are significant at part loads. In sailing mode, the minimum efficiency improvements are close to 2 % at maximum speed or rated load. This improvement is lower than increment calculated at rated load in subsection 3.3 due to the additional efficiency losses in the electrical system, which were not accounted for earlier. Thus, it is vital to account for these losses when investigating the potential of electrical architectures and/or SOFC-ICE integration. The improvements at rated load during combat mode were about 2 to 3 %. The efficiency improvements due to the CFb and FFb method amount to potential CO_2 reductions of about 30 % and 40 %, respectively, during both the modes.

As seen from Figure 9(b) and Figure 10(b), significant efficiency improvements could be attained via the COFAICE system employing SOFC-ICE integration for naval applications. While the efficiency improvements indicated by the CFb method may be currently achievable, FFb method indicates the untapped potential of SOFC-ICE integration, which can initiate a paradigm shift in ship performance and operations. Therefore, further research is recommended to investigate the development of AOG-NG flexible-fuel blend engines for SOFC-ICE integration. Additionally, although the research presented in this paper on natural gas-fuelled SOFC-ICE systems, further research should be performed into methanol and ammonia-fuelled SOFC-ICE power plants due to their promise of very low emissions and high-efficiency operation.

5 Conclusions

In this paper, the potential of a novel COmbined drive of Fuel cell And Internal Combustion Engine (COFAICE) system was studied for three case studies of naval vessels, namely, an oceangoing patrol vessel, a landing platform dock and a high-speed surface combatant. The proposed COFAICE system employs a solid oxide fuel cell (SOFC) in serial integration with an internal combustion engine (ICE) for naval power generation. Using the operational profiles of the vessels, optimal load sharing strategies between the two energy conversion devices were investigated for the three cases studies. Based on the optimal power split, potential of two SOFC-ICE integration methods were

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investigated for part-load operations of case study 3. The main conclusions drawn from this investigation are as follows:

- In this study, optimal SOFC-ICE power splits were computed to achieve high system efficiency with lowest system weight and size requirements (including fuel bunkering). The optimal SOFC-ICE power split for the oceangoing patrol vessel was found to be 28-72, for the landing platform dock it was 55-45 and for the high-speed surface combatant, it was 27-73.
- The computed optimal power splits resulted in system efficiency improvements of 9 to 11 % at rated operating conditions compared to current systems onboard the case studies. Additionally, SOFC-ICE integration also showed potential emission reductions in the range of 36 to 43 % for the three case studies.
- Next to the improvements in power-generation efficiency and CO_2 emissions, the SOFC-ICE system was found to be about 3.7 times bigger and 2 times heavier compared to the current system for case study 2 due to the larger SOFC load share. In case of case study 1 and 3, the system volume increased by 2 times but weight increased by a maximum of 1.08 times.
- For part load operations, the constant fuel blend (CFb) method for SOFC-ICE integration showed efficiency improvements of up to 8 % while the flexible fuel blend (FFb) method indicated improvements of more than 20 % compared to the original system for both the sailing and combat modes of the high-speed surface combatant (HSC).
- In sailing and combat mode of the HSC, the minimum efficiency improvements for SOFC-ICE integration were about 2 to 3 % at maximum speed or rated load. This improvement was lower than the earlier found increment of about 9 % for case study 3 due to the additional efficiency losses in the electrical system, which were not accounted for in the earlier calculations. Thus, it is vital to account for these losses when investigating the potential of SOFC-ICE integration.
- The efficiency improvements indicated by the CFb method may be currently achievable while the FFb method shows the untapped potential of SOFC-ICE integration, which can initiate a paradigm shift in naval ship performance and operations.
- Overall, the results show that significant improvements in naval ship performance could be gained by integrating a smaller load share SOFC with an ICE while leveraging relatively smaller increments in system specifications. These increments in volume and weight for SOFC-ICE integration could pose a challenge with respect to ship design and limit the possibilities for it to act as a direct 'drop-in' for current configurations. The authors are hopeful that increasing research and implementation will lead to improved scaling and broader application of this technology as a whole.

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A Data assumptions for calculations

Table A.1: Assumed power densities of SOFC, the integrated ICE operating on AOG-NG fuel blends, diesel generator sets and high-speed diesel (HSD) engines

Component	Volumetric power density [$W L^{-1}$]	Gravimetric power density [$W kg^{-1}$]
SOFC	10.11	20.93
ICE	72.05	84.3
High-speed DG for case study 1 and 3	67.89	80.16
Low-speed DG for case study 2	45.08	61.52
HSD for case study 1 and 3	94.21	142.85

Table A.2: Assumed specific fuel consumption (sfc) and efficiencies of high-speed diesel generator sets for case study 1 and 3

Load [%]	sfc [$g kW^{-1} h$]	Efficiency [%]
10	377	22.28
25	267.6	31.39
50	230.6	36.43
75	221.4	37.94
100	209.4	40.11

Table A.3: Assumed specific fuel consumption and efficiencies of low-speed diesel generator sets for case study 2

Load [%]	sfc [$g kW^{-1} h$]	Efficiency [%]
10	261	32.18
50	187	44.92
100	177	47.46

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Table A.4: Assumed specific fuel consumption and efficiencies of high-speed diesel engines for case study 1 and 3

Load [%]	sfc [$g\,kW^{-1}\,h$]	Efficiency [%]
10	233.2	36.02
20	223.2	37.63
30	214.9	39.08
40	210	40
50	204.2	41.13
60	200.1	41.97
70	196.7	42.70
80	194.1	43.27
90	192.6	43.61
100	195	43.07

Table A.5: Assumed efficiencies of NG-fuelled ICE for SOFC-ICE integration. When the ICE runs on a 30-70 AOG-NG fuel blend, a 2 % efficiency improvement is added to the values

Load [%]	Efficiency [%]
10	20.5
25	31.87
50	39.04
75	42.20
90	43.38
100	44

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