

Research paper

Comprehensive techno-economic assessment of SOFC hybrid system in marine applications: A carbon emission framework perspective

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ABSTRACT

This study investigates the techno-economic feasibility of a hybrid electric propulsion system that integrates solid oxide fuel cells (SOFC), energy storage systems (ESS), and dual fuel generators (DF Gen) for large commercial vessels. A 20-year operational analysis was conducted using 500 h load profiles from a 174,000 m³ liquefied natural gas (LNG) carrier. Carbon dioxide (CO₂) emissions and total cost of ownership (TCO) were assessed under varying SOFC capital costs, carbon tax levels, and fuel prices within a full carbon life-cycle framework. Unlike conventional approaches that consider only Tank-to-Wake (TTW) emissions, this study adopts a Well-to-Wake (WTW) and CO₂-equivalent perspective to comprehensively evaluate greenhouse gas impacts. The results show that the SOFC + ESS hybrid system improves electrical efficiency and achieves CO₂ emission reductions of up to 3 % compared with conventional mechanical propulsion systems under TTW conditions. When the analysis expands to include WTW CO₂-equivalent emissions based on a 20-year global warming potential (GWP20), the reduction reaches approximately 30 %. Economic competitiveness is sensitive to multiple parameters, including SOFC capital cost, carbon tax level, and fuel price, and the hybrid system becomes favorable under scenarios with higher carbon tax or reduced SOFC investment cost. Although the SOFC hybrid cannot fully meet the International Maritime Organization (IMO) 2050 decarbonization target when operated on fossil fuels alone, it represents a promising transitional technology—particularly when combined with carbon capture or carbon-neutral fuels such as ammonia or hydrogen.

1. Introduction

The maritime industry is under increasing pressure to reduce greenhouse gas (GHG) emissions in accordance with the International Maritime Organization (IMO) decarbonization strategy, which aims for a 20–30 % reduction by 2030 and net-zero emissions by 2050 relative to 2008 levels (IMO, 2023). These targets have accelerated the transition toward low- and zero-emission propulsion technologies, as conventional mechanical propulsion systems powered by large two-stroke diesel engines remain the dominant source of carbon dioxide (CO₂) emissions in maritime transport. The adoption of liquefied natural gas (LNG) as a transitional marine fuel has reduced sulfur oxide (SO_x) and nitrogen oxide (NO_x) emissions; however, its combustion still produces substantial CO₂ and methane (CH₄) emissions. Therefore, the development of

next-generation energy systems that can deliver both high efficiency and deep decarbonization is becoming increasingly important.

Various alternative technologies have been proposed to achieve maritime decarbonization, including battery-electric systems, hybrid propulsion systems, and fuel cell-based power generation. Battery systems offer zero local emissions but are constrained by limited energy density and long charging times, restricting their use to short-range operations. Dual-fuel (DF) engines operating with LNG have been adopted as an intermediate solution, offering lower Tank-to-Wake (TTW) CO₂ emissions than heavy fuel oil engines. However, their overall environmental performance remains inadequate for meeting future Well-to-Wake (WTW) emission standards. In this context, hybrid energy systems integrating fuel cells and energy storage systems (ESS) have gained attention as a potential pathway to bridge the gap between

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conventional mechanical propulsion and fully carbon-neutral solutions.

Among various fuel cell technologies, the solid oxide fuel cell (SOFC) stands out for its high electrical efficiency, fuel flexibility, and compatibility with existing LNG infrastructure. SOFC can operate directly on LNG through internal reforming, enabling simple integration with shipboard fuel systems. Moreover, the high exhaust temperature of SOFC allows for waste heat recovery, improving the overall energy efficiency of the system. These characteristics make SOFC particularly suitable for large commercial vessels with continuous high power demand, where thermal management and fuel efficiency are critical.

Several researchers have examined the application of hybrid fuel cell systems for maritime power generation. Livanos et al (Livanos et al., 2014), assessed the use of waste heat recovery systems in conventional ferry propulsion plants within Emission Control Areas (ECA), focusing on improving the efficiency of reciprocating engines. Tzannatos et al (Tzannatos et al., 2015), evaluated the cost-effectiveness of using LNG as a dual-fuel option for Greek island ferries. Following the adoption of LNG, recent studies have explored more advanced low-carbon configurations. Wang et al (Wang et al., 2024), compared different fuel cell types and proposed the most efficient configurations based on power density and emissions. Yuksel et al (Yuksel, 2023), developed a hybrid system that combines dual-fuel engines with SOFC and a waste heat recovery unit to enhance energy efficiency. Oh et al (Oh et al., 2023), proposed a combined electrical and thermal energy recovery approach, achieving a 22 % improvement in overall efficiency. Li et al (Li et al., 2024), optimized battery-supercapacitor energy storage configurations through multi-objective optimization, and Xie et al (Xie et al., 2023), demonstrated that predictive energy management for PEMFC–battery hybrid systems could improve fuel efficiency by 23 %.

Although these studies have advanced hybrid propulsion research, most have focused solely on Tank-to-Wake (TTW) carbon emissions, neglecting upstream emissions associated with fuel production, processing, and distribution. Oh et al (Oh et al., 2024), and Zamboni et al (Zamboni et al., 2024), addressed this gap by evaluating Well-to-Wake (WTW) emissions, which encompass the entire lifecycle from fuel extraction to consumption. However, existing studies remain limited in their incorporation of practical operational data and long-term economic assessment, particularly for large-scale SOFC-based hybrid systems. There is still a lack of quantitative research combining real vessel operating profiles, multi-decade techno-economic evaluation, and lifecycle GHG assessment.

The present study addresses this gap by conducting a comprehensive techno-economic assessment of a hybrid electric propulsion system integrating SOFC, ESS, and DF generators (DF Gen) for large liquefied natural gas carriers. Using actual 500-hour load profiles recorded from a 174,000 m³ LNG carrier, the analysis estimates fuel consumption, CO₂ emissions, and the 20-year total cost of ownership (TCO) under varying SOFC degradation rates, fuel price conditions, and carbon tax levels. Both TTW and WTW emission frameworks are considered to evaluate the system's environmental performance. Furthermore, the calculated CO₂ emissions are compared with the IMO's mid-term reduction roadmap adopted at the 83rd Marine Environment Protection Committee (MEPC 83) meeting. To the authors' knowledge, this is the first study to combine real operational data with a full-lifecycle techno-economic analysis of an SOFC–ESS–DF Gen hybrid system for large vessels. The results provide new insights into the transitional role of SOFC-based propulsion systems and their potential integration with carbon capture and carbon-neutral fuels such as ammonia or hydrogen to achieve future decarbonization goals.

2. Methodology

This section describes the methodological framework adopted to evaluate the techno-economic performance of the SOFC–ESS–DF generator hybrid system. First, the operational load profile of an LNG carrier is introduced, followed by the configuration of the three

alternative power generation systems. Next, the cost and degradation assumptions for SOFC stacks and ESS are outlined, and finally, the life-cycle emission accounting and Total Cost of Ownership (TCO) assessment procedures are explained. This provides the basis for a comprehensive comparison across different propulsion scenarios under current and future regulatory conditions.

2.1. System configuration

The total power demand for propulsion in the vessels being studied equals the energy needed to operate the vessel for a period of 20 days, as depicted in Fig. 1. The load profile analyzed in this research includes the main engine output and power load information of 174,000 m³ LNG carriers operated by a specific shipping company from August to September 2019. The power requirements for operation are supplied by three types of power generation systems, and optimal energy is distributed among each power source in the power generation system according to the SQP operation strategy suggested by Lee et al (Lee et al., 2025). The optimization problem formulated in this study involves nonlinear relationships and operational constraints resulting from SOFC degradation, ESS cycling limits, and carbon tax scenarios. To solve such nonlinear constrained problems, the Sequential Quadratic Programming (SQP) method was applied, following the strategy of Lee et al (Lee et al., 2025). SQP is particularly suitable for constrained nonlinear optimization because it provides reliable convergence while ensuring that system constraints are satisfied. The three types of power generation systems are as follows.

- DF Gen only system: Dual Fuel Generator (DF Gen)
- ESS Hybrid system: Dual Fuel Generator (DF Gen) and Energy Storage System (ESS)
- SOFC Hybrid system: Dual Fuel Generator (DF Gen), Energy Storage System (ESS), and SOFC

The first case, DF Gen serves as the sole power source. The second case involves combining the DF Gen and ESS. The DF Gen supplies consistent power, while the ESS handles varying loads. The DF Gen and ESS operate in the direction of minimizing an objective function that has the system's fuel consumption and the battery's state of charge (SOC) as variables. Hence, the fuel consumption and the functional value of the engine's SOC are considered as important variables. The third case consists of the integration of the DF Gen with the SOFC – ESS system. The engine and fuel cells generate the required power, whereas the battery manages fluctuating loads. Similar to the second case, the DF Gen, SOFC, and ESS function to minimize the objective function which includes fuel consumption of the system and state of charge of the

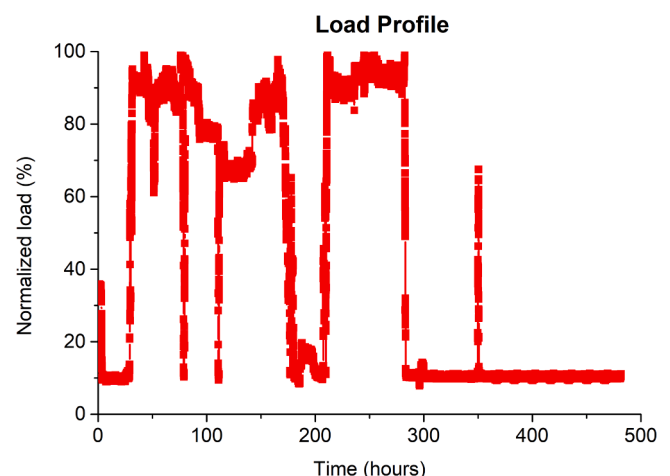


Fig. 1. Load profile of the 174,000 m³ LNG carrier.

Table 1

System configuration and components capacity for each case.

	DF Gen only	DF Gen + ESS	DF Gen + ESS + SOFC
DF Gen	23 MW	23 MW	21 MW
ESS	-	4 MWh	4 MWh
SOFC	-	-	2 MW

battery as variables. The system capacity for each case is presented in Table 1.

2.2. Design basis and components

The Total Cost of Ownership (TCO) includes not only the initial purchase price of a product, but also all additional costs accumulated throughout its operational duration. In order to make an accurate estimation of the Total Cost of Ownership, it is necessary to take into account the following components:

- Thorough assessment of expenses accrued over the full duration of the product's life cycle.
- Combining the initial capital expenditure (CAPEX) of the product with ongoing operational expenses in order to calculate the total ownership cost.

The initial cost was determined based on the capital investment needed for crucial system components such as the SOFC, ESS, and DF Gen. Furthermore, the analysis included operational costs over the life cycle, including expenses related to gas price, oil price, and carbon tax. Degradation of both the battery and the SOFC stack was also taken into account due to its influence on fuel efficiency and overall operating costs. To estimate future expenses in present value terms, an annual discount rate of 3 % was applied.

$$TCO = CAPEX + \sum_{n=1}^{n=20} OPEX$$

$$CAPEX = CAPEX_{DF\ Gen} + CAPEX_{ESS} + CAPEX_{SOFC}$$

$$OPEX = OPEX_{fuel} + OPEX_{CO2} + OPEX_{replacement}$$

$$OPEX_{fuel} = OPEX_{fuel,DF\ Gen,GAS} + OPEX_{fuel,DF\ Gen,OIL} + OPEX_{fuel,SOFC,GAS}$$

$$OPEX_{CO2} = OPEX_{CO2,DF\ Gen} + OPEX_{CO2,SOFC}$$

$$OPEX_{replacement} = OPEX_{replacement,SOFC} + OPEX_{replacement,BAT}$$

2.3. Dual fuel generator price

The price of the DF Gen, which is fueled by liquefied methane, was assumed to be 470 USD/kW (Korberg et al., 2021). Similar to the DF Gen, the SOFC system also utilizes liquefied methane as its fuel, which is supplied in a vaporized form. Therefore, the fuel gas supply system required for handling liquefied methane was excluded from the scope of the economic evaluation for both systems.

2.4. SOFC price

The capital cost of the SOFC system was estimated considering current large-scale commercial project data. A unit cost of approximately 72.4 million USD was adopted for a 19.8 MW installation, which corresponds to the most recently reported project scale of a domestic SOFC power plant. This cost reference was derived from the Credit Rating Report published by Korea Investors Service (KIS, 2024), which evaluated the SE Green Energy 19.8 MW SOFC project (KIS, K.I.S., 2024). The derived specific cost (3660 USD/kW) was then used as the baseline for capital expenditure (CAPEX) estimation in the present analysis. The fuel

cell system is composed of the SOFC stack and supporting subsystems. According to a cost analysis conducted by the Battelle Memorial Institute on a 100 kW combined heat and power (CHP) SOFC system, the power control unit represents the largest portion of the total cost, accounting for approximately 35 % (Institute, 2016). The SOFC stack comprises approximately 27–32 % of the total system cost. In this study, a stack cost ratio of 30 % was assumed for the economic analysis.

2.5. ESS price

In recent years, the electric vehicle (EV) market has continued to expand, with transportation electrification extending beyond passenger vehicles to include electric bikes, ships, and even aircraft. The global production capacity of lithium-ion batteries (LiBs) in 2022 was approximately 1.6 TWh, and it is projected to reach around 6.8 TWh by 2030 (Agency, 2023). This significant increase in production capacity, driven by mass production and technological advancements, is expected to lead to a gradual decrease in battery prices. Orange et al. estimated the cost of battery cell production using a component-based approach that factors in material costs, technical specifications, and manufacturing requirements, projecting a cost range of 48.6–57.9 USD/kWh by 2030 (Orangi et al., 2024). Additionally, Lowe et al. reported that battery cells typically account for about 45 % of the total cost of a battery pack when commercialized (Lowe et al., 2010). Based on this information, the cost of battery packs in 2030 is expected to range between 110 and 130 USD/kWh. In this study, a cost of 110 USD/kWh was used in the total cost of ownership (TCO) calculations.

2.6. SOFC degradation rate

Stack degradation in SOFC is a critical factor influencing their economic viability. As SOFC performance declines due to degradation, the electrical efficiency of the system decreases gradually. When the efficiency decreases compared to traditional power generation technologies, the amount of fuel needed to generate a specific amount of electricity rises, subsequently increasing operational expenses. If this situation continues, SOFC become economically disadvantaged in comparison to conventional energy sources. As a result, it is necessary to replace the SOFC stack once its efficiency decreases below a certain threshold where it no longer provides a cost benefit.

According to a cost breakdown conducted by the Battelle Memorial Institute (Institute, 2016), the SOFC stack constitutes approximately 30 % of the total module cost. Based on the estimated price per kilowatt for SOFC systems, this corresponds to a stack cost of roughly USD 1100/kW. If fast deterioration is expected, additional stack replacements will be necessary, leading to a notable rise in operational costs. Consequently, rising costs associated with degradation present a significant barrier to the widespread adoption of SOFC technology. (Whiston et al., 2019, Skafte et al., 2016))

Ceres Power (UK) reports a degradation rate of 1 % per 1000 operating hours for its compact SOFC systems (McPhail et al., 2017). Meanwhile, projected average degradation rates for SOFC stacks are 0.5 %/1000 h in 2020, 0.3 %/1000 h by 2035, and 0.2 %/1000 h by 2050. In this study, an economic evaluation was conducted using degradation scenarios of 0.5 %/1000 h (Golkhatmi et al., 2022) and 0.2 %/1000 h (Iyengar et al., 2022) to assess their impact on long-term cost-effectiveness.

2.7. ESS degradation rate

The decline in battery capacity, known as battery degradation, results from various physical and chemical processes. According to Vetter et al., the decline in capacity is largely attributable to the deterioration of the positive electrode, negative electrode, and electrolyte over time (Vetter et al., 2005). The decline is caused by intricate electrochemical reactions taking place within the cell, leading to extensive investigation

into analytical models that replicate these internal processes. Nevertheless, models that include intricate electrochemical processes demand significant computational power and analytical capabilities. In order to address these limitations, several studies have suggested using empirical degradation models based on experimental data, which can be utilized to predict capacity with lower computational requirements. (Forman et al., 2012; Li et al., 2011)

Wang et al. investigated the impact of various operating conditions—including current, state of charge (SOC), and cycling intervals—on capacity loss in a LiMnNiCo/LiMn₂O₄ battery system, enabling predictive modeling of charge degradation (Wang et al., 2014). Fortenbacher et al. further advanced this approach by normalizing battery operating parameters and generating a degradation map, thereby enabling capacity loss prediction independently of specific battery system sizes (Fortenbacher and Andersson, 2017). Based on the degradation equation proposed by Fortenbacher et al., the total capacity loss of a battery pack was quantified in terms of energy per unit time (kWh/h).

2.8. Fuel price

The LNG bunkering price in Rotterdam over the past year (June 30, 2023 – June 30, 2024, Fig. 2) ranged from 531 USD/ton to 999 USD/ton, with an average price of approximately 704 USD/ton (Bunker, 2024). Additionally, the price of oil fuel—supplied in small quantities to ensure the combustion stability of the DF Gen—ranged from 701 USD/ton to 996 USD/ton during the same period, with an average of approximately 814 USD/ton. In this study, the economic feasibility of the hybrid system was evaluated across a range of fuel gas prices, using 700 USD/ton for LNG and 880 USD/ton for oil fuel as reference values.

2.9. Life cycle emissions of greenhouse gases

The Energy Efficiency Design Index (EEDI) has been implemented by the International Maritime Organization (IMO) since 2011 to decrease CO₂ emissions in the maritime transport industry. The EEDI governs the amount of CO₂ emissions produced per metric ton of cargo carried over a single nautical mile, with variations based on the type of cargo being transported. The CO₂ emission limits are gradually reduced in stages, with 2008 levels serving as the initial reference point.

Nevertheless, the EEDI is founded on a tank-to-wake (TTW) methodology, which solely accounts for emissions emitted during fuel combustion while disregarding those originating from the fuel production process. Additionally, it only governs CO₂ emissions, while disregarding other important greenhouse gases like methane (CH₄), nitrous oxide (N₂O), and black carbon. In order to achieve more comprehensive

climate goals, regulatory frameworks should shift towards well-to-wake (WTW) standards that consider greenhouse gas emissions across the entire fuel lifecycle, and towards CO₂-equivalent (CO₂-eq) metrics that include non-CO₂ climate pollutants.

As shown in Table 2, a high-pressure, two-stroke Dual Fuel Main Engine that operates on LNG using the diesel cycle emits approximately 2.7 tons of CO₂ per ton of LNG consumed, based on the tank-to-wake (TTW) approach (Comer and Osipova, 2021). In contrast, a WTW evaluation results in 3.28 tons of CO₂. The total greenhouse gas emissions in CO₂-equivalent is calculated as 3.94 tons CO₂-eq based on a 100-year Global Warming Potential (GWP100), and 5.008 tons CO₂-eq based on a 20-year GWP (GWP20). The higher value for GWP20 is due to methane's short atmospheric lifespan (approximately 9–12 years), during which it exerts a more intense warming effect. Consequently, its GWP20 value is 85, significantly higher than its GWP100 value of 30.

This study examines the GHG emissions not only in the current EEDI standard but also extends the comparison to include the WTW-based carbon factor and CO₂-equivalent emissions under both 20-year and 100-year GWP. This approach anticipates upcoming regulatory shifts and provides a more comprehensive assessment of GHG impacts.

2.10. Maintenance schedule

Performance degradation occurs due to SOFC and battery degradation. Therefore, the SOFC and battery need to be replaced at a specific point in time. In the event of a system replacement, the total cost of ownership is affected. This study examines the performance degradation of three types of hybrid electric propulsion systems over time and evaluates the impact. A large vessel is projected to operate 17 voyages annually over a 20-year service life, based on a defined operational profile (Fig. 1). When the fuel cell stack degradation rate is assumed to be −0.5 % per 1000 h, analysis indicates that the fuel cell stack would require replacement after approximately 7 years of operation. As illustrated in Fig. 3, the ratio of gas consumption between the SOFC system and the DF Gen remains relatively stable during the first six years. Nevertheless, a steady rise in gas consumption by the fuel cell can be observed, which can be attributed to incremental efficiency decreases caused by degradation. After year 7, there is a notable rise in fuel consumption of the DF Gen, while the power output of the SOFC decreases significantly. This transition indicates when the efficiency of the fuel cell decreases compared to that of the DF Gen, leading to a transfer of the power generation responsibility. As a result, a larger portion of electrical energy that was previously provided by the SOFC is now produced by the DF Gen. In contrast, with a degradation rate of −0.2 % per 1000 h, the point at which fuel cell efficiency drops below that of the DF Gen is delayed to around year 16 of operation. The replacement intervals for the fuel cell stack are assumed to be at 7 and 14 years in the case of a degradation rate of −0.5 %, and at year 10 in the case of a degradation rate of −0.2 %, based on these scenarios.

Regarding the ESS, degradation estimates derived from the vessel's operational profile suggest a gradual capacity decline over the 20-year period. As shown in Fig. 4, the ESS is expected to retain approximately 74 % of its original capacity after two decades, corresponding to an average annual degradation rate of approximately 1.3 %. Since the ESS does not generate energy but rather stores and discharges it, it is assumed that replacement will be required after 10 years of operation.

The DF Gen is projected to have a similar lifespan to the vessel and is therefore not expected to need replacement within the 20-year operational period. Fig. 5 outlines the timelines for the replacement of the SOFC, ESS, and DF Gen.

2.11. Summary

All figures presented in the Results and Discussion section were generated within the methodological framework described above. The operational load profiles in Fig. 1 were obtained from the actual engine

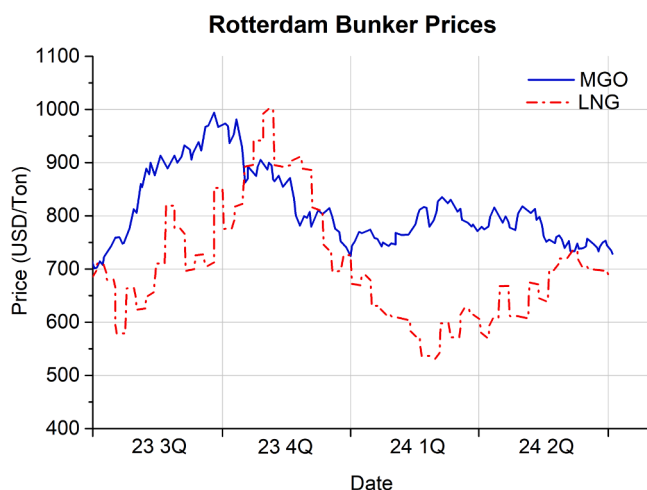


Fig. 2. LNG and MGO bunker price at the Rotterdam.

Table 2
Carbon factors based on the fuel types, engine types, and carbon life cycle (Source: [Comer and Osipova 2021](#) ([Comer and Osipova, 2021](#))).

Fuel	Engine	Tank to Wake (TTW)			Well to Wake (WTW)		
		CO ₂	CO _{2eq100}	CO _{2eq20}	CO ₂	CO _{2eq100}	CO _{2eq20}
LNG	Diesel cycle	2.750	2.864	2.965	3.280	3.940	5.008
	2 stroke						
	Otto cycle	2.750	3.308	4.244	3.280	4.385	6.288
	2 stroke						
	Otto cycle	2.750	3.854	5.758	3.280	4.930	7.801
MGO	4 stroke						
	Fuel cell	2.750	2.750	2.750	3.280	3.828	4.795
	2 stroke	3.206	3.284	3.357	3.782	4.007	4.340
	4 stroke	3.206	3.408	3.802	3.782	4.130	4.785

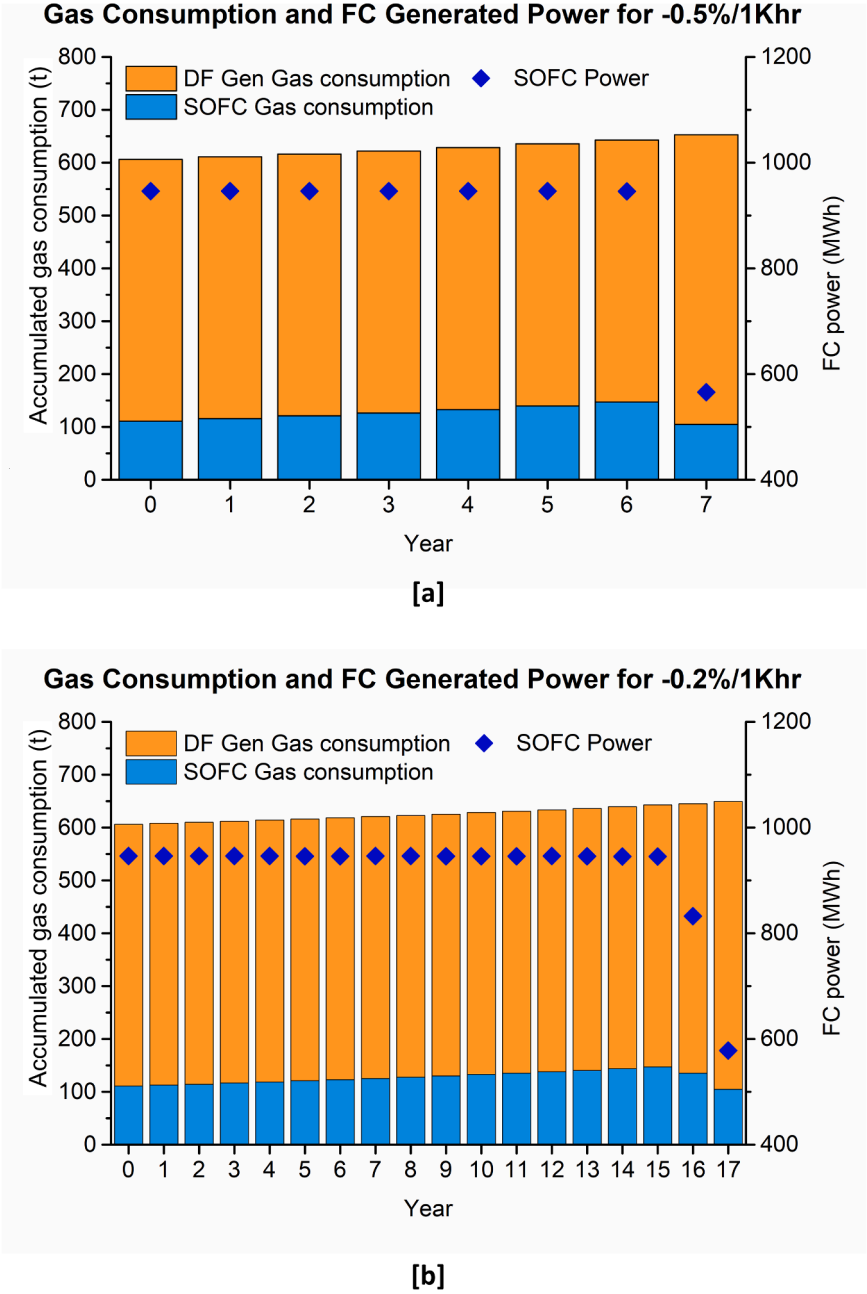


Fig. 3. Accumulated gas consumption and FC generated power for [a] $-0.5\%/1000$ hr, [b] $-0.2\%/1000$ hr.

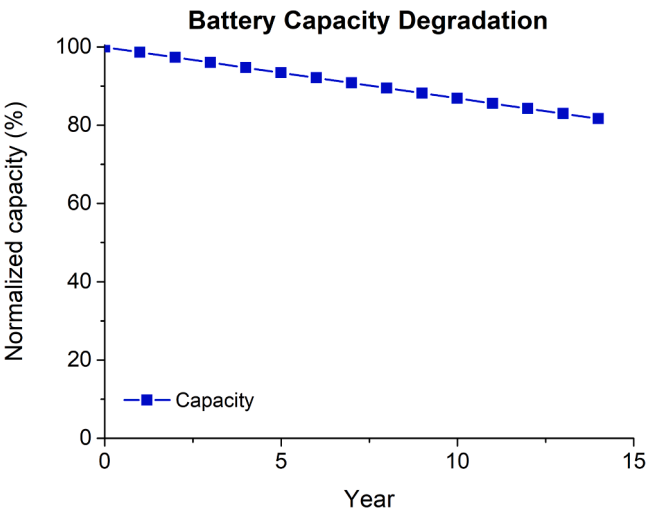


Fig. 4. Expected battery capacity considering degradation.

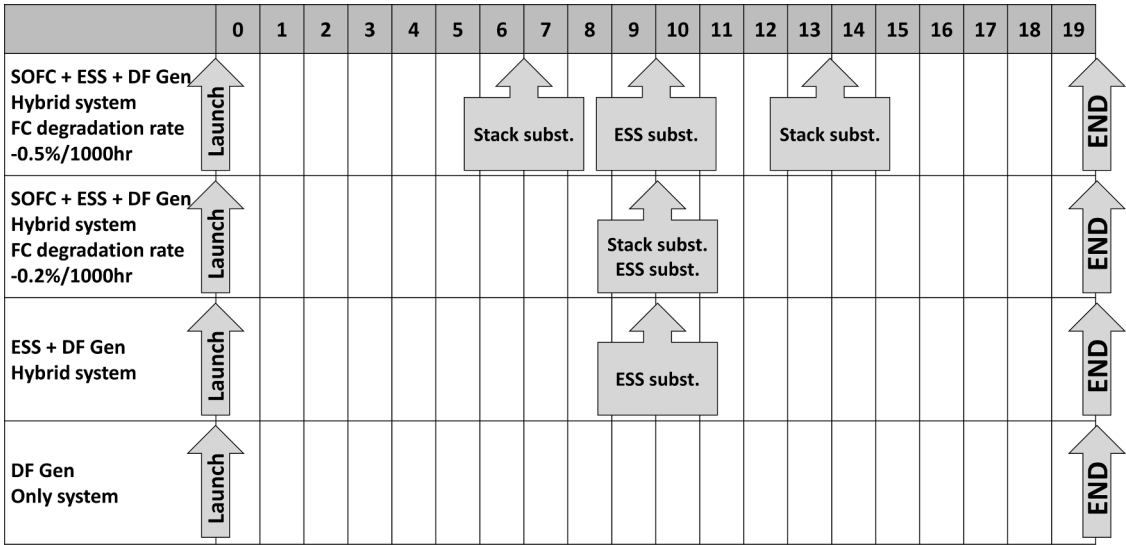


Fig. 5. Maintenance schedule of major equipment.

and auxiliary power data of a 174,000 m³ LNG carrier recorded during August–September 2019. System configurations and component ratings (Table 1) were applied to simulate the three alternative propulsion cases (DF Gen only, DF Gen + ESS, and DF Gen + ESS + SOFC). Figs. 6–9 were derived by calculating the Total Cost of Ownership (TCO) under varying carbon tax levels, fuel prices, and SOFC capital costs, using the economic assumptions summarized in Section 2.2 with a 3 % annual discount rate. Figs. 10–11 were produced by applying the 500-hour operational profile to various SOFC capacity, with greenhouse gas factors and global warming potentials (GWP20 and GWP100) taken from Table 2. Finally, Fig. 12 was generated by comparing the simulated Well-to-Wake CO₂-equivalent emissions against the IMO mid-term GHG reduction targets adopted at MEPC 83. All calculations were performed in MATLAB, and the plotted results are based on the replacement assumptions for SOFC stacks and ESS outlined in Section 2.10.

The selection of control parameters applied in this study was guided by a combination of operational data, literature references, and design feasibility considerations. The SOFC system capacity was set at 2 MW to represent approximately 40 % of the vessel’s average propulsion load, reflecting both the scalability limits of current stack modules and the

configurations suggested in previous techno-economic assessments (e.g., Yüksel et al., (Yüksel, 2023)). The ESS capacity of 4 MWh was chosen to enable effective load-leveling during transient operations while remaining consistent with the scale of commercially available marine battery systems.

For SOFC degradation, two scenarios were introduced: −0.5 %/1000 h and −0.2 %/1000 h efficiency decline. These values were derived from empirical ranges reported in prior studies (Skafte et al., (Skafte et al., 2016); Golkhatmi et al., (Golkhatmi et al., 2022)), and they represent pessimistic and optimistic assumptions, respectively. The ESS degradation model was parameterized using a degradation map that incorporates the aging of the anode, cathode, and electrolyte, which reflects well-established patterns observed in lithium-ion batteries under partial-state-of-charge cycling.

Economic parameters such as carbon tax levels (0–500 USD/ton) and LNG prices (500–1500 USD/ton) were selected to capture both the anticipated range of future IMO regulatory scenarios and the historical volatility of marine fuel markets. Finally, operational load profiles used to calibrate the model were obtained from the actual engine and auxiliary power logs of a 174,000 m³ LNG carrier during

TCO ratio of SOFC hybrid system over DF Gen only system (Tank to Wake)

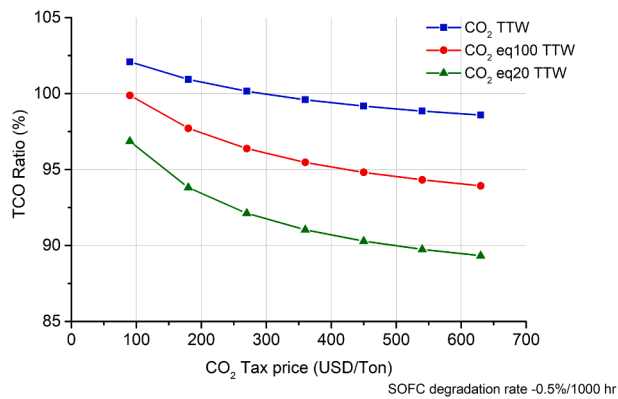


Fig. 6. TCO ratio of SOFC hybrid system over DF Gen only system (Tank-to-Wake).

August–September 2019, ensuring that the chosen parameters represent realistic vessel operating conditions.

3. Result and discussion

3.1. Analysis of TCO impact by carbon life cycle

DF Gen exhibit higher levels of incomplete combustion, such as methane slip, compared to high-pressure (HP) two-stroke main engine operating on the Diesel cycle or low-pressure (LP) two-stroke main engine operating on the Otto cycle. Therefore, DF Gen exhibit comparatively elevated CO₂-equivalent emissions (CO_{2,eq100} and CO_{2,eq20}), as depicted in Table 2. On the other hand, SOFC fueled by LNG are known to operate without methane slip or similar incomplete combustion phenomena (Van Veldhuizen et al., 2023).

As a result, when greenhouse gas emissions are evaluated using CO₂-equivalent metrics — such as CO_{2,eq20} and CO_{2,eq100} — that consider the climate impact of methane (CH₄) and nitrous oxide (N₂O) in addition to CO₂, the cost penalty associated with carbon taxation increases significantly for systems with higher non-CO₂ emissions. Thus, as depicted in Fig. 6, the Total Cost of Ownership (TCO) of the SOFC hybrid system is lower than that of a DF Gen only system, due to its significantly lower emissions of CH₄ and N₂O. This illustrates the efficient cost performance of the SOFC hybrid system when considering a full assessment of carbon emissions.

When taking into account solely the emissions of CO₂, the economic feasibility of the SOFC hybrid system surpasses that of DF Gen only system once the carbon tax surpasses about 300 USD/ton. However,

TCO ratio of SOFC hybrid system over DF Gen only system (Well to Wake)

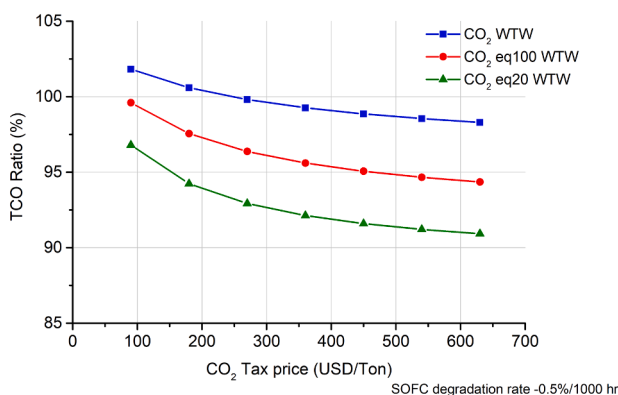


Fig. 7. TCO ratio of SOFC hybrid system over DF Gen only system (Well-to-Wake).

TCO ratio according to Gas price

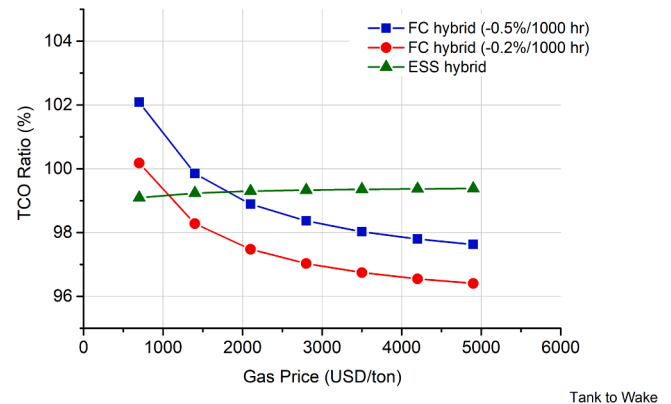


Fig. 8. TCO ratio of SOFC hybrid system over DF Gen only system according to the fuel price.

when CO₂-equivalent metrics (CO_{2,eq20} and CO_{2,eq100}) are applied, taking into account the global warming potential of CH₄ and N₂O, the SOFC hybrid system demonstrates cost-effectiveness even at the current CO₂ tax level of 100 USD/ton.

Current carbon emissions are commonly calculated using the tank-to-wake (TTW) standard, which accounts solely for emissions produced from fuel combustion aboard the vessel. If regulatory standards transition to the well-to-wake (WTW) methodology, considering emissions throughout the fuel production and supply chain processes, there is an observed increase in the CO₂ emissions per ton of LNG. This change also improves the comparative economic viability of SOFC hybrid systems. For example, in the scenario where a carbon dioxide tax is exclusively imposed on tank-to-wake emissions, the cost at which the SOFC hybrid system becomes financially competitive with four-stroke engines is 300 USD/ton. Under a well-to-wake framework, this threshold lowers to 250 USD/ton. Moreover, when all greenhouse gases — including CH₄ and N₂O — are included, the SOFC hybrid system becomes more competitive even at current CO₂ tax levels, as demonstrated in Fig. 7. Our analysis indicates that SOFC hybrids become cost-competitive when the carbon tax exceeds ~250 USD/ton under a WTW framework. Similar thresholds have been reported by Zamboni et al (Zamboni et al., 2024), who emphasized that the inclusion of CH₄ and N₂O substantially shifts the break-even point of alternative propulsion systems under carbon pricing schemes, supporting the robustness of our finding. This confirms that economic viability is strongly policy-dependent, particularly in the near term.

TCO ratio according to FC price

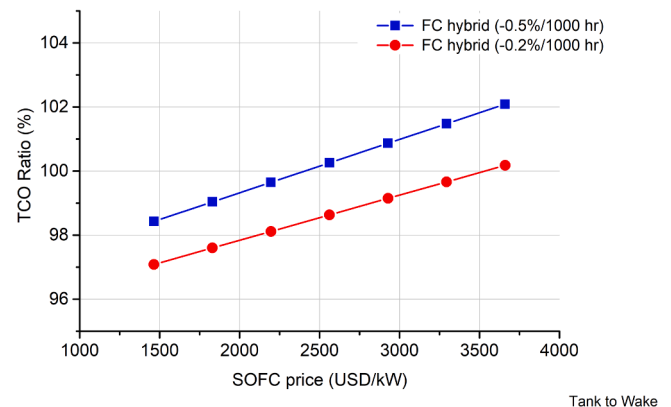


Fig. 9. TCO ratio of SOFC hybrid system over DF Gen only system according to the SOFC price.

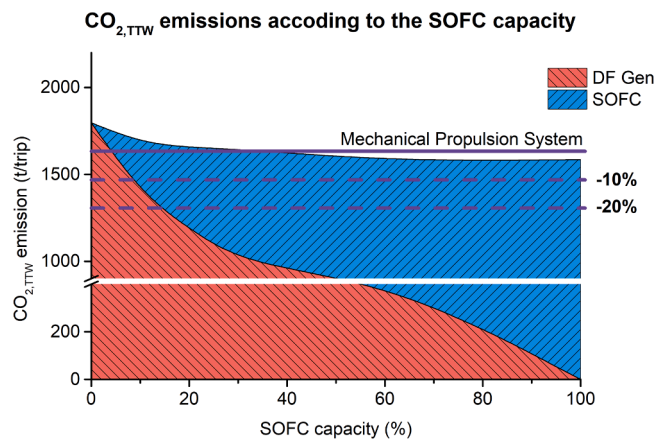


Fig. 10. CO₂ emissions according to the SOFC Capacity.

3.2. Analysis of TCO impact by fuel price

The graph in Fig. 8 demonstrates a similar trend in the impact of fuel price fluctuations on the total cost of ownership (TCO) as observed in the previous analysis of carbon taxes. At the present baseline price of LNG fuel, which is set at 700 USD/ton, the total cost of ownership for the SOFC hybrid system is predicted to surpass that of the DF Gen alone setup. Nevertheless, the increasing prices of LNG fuel contribute to the improved cost competitiveness of the SOFC-based system compared to the GE-only system due to its superior efficiency.

More precisely, at the assumed rate of SOFC degradation of -0.5% per 1000 operating hours, the economic viability of the SOFC hybrid system is achieved when prices of LNG exceed around 1400 USD/ton. The impact of SOFC degradation on long-term viability observed in this study is consistent with findings from Skafte et al (Skafte et al., 2016). and Golkhatmi et al (Golkhatmi et al., 2022)., who emphasized that stack durability remains a key determinant of economic feasibility.

Moreover, with the rise in LNG fuel prices, operating expenditures (OPEX) begin to account for a greater proportion of the total cost of ownership. As a result, the difference in total cost of ownership across system configurations becomes similar to the difference in operating expenses.

3.3. Analysis of TCO impact by SOFC price

In the higher degradation rate scenario ($-0.5\%/1000$ h), the SOFC stack needs to be replaced twice in the 20-year operation period, whereas in the lower degradation rate scenario ($-0.2\%/1000$ h), it only needs to be replaced once, resulting in a maintenance cost that varies

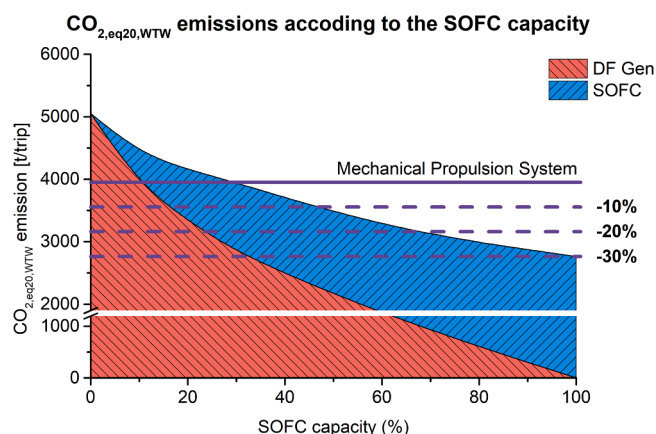


Fig. 11. CO_{2,eq20,WTW} emissions according to the SOFC Capacity.

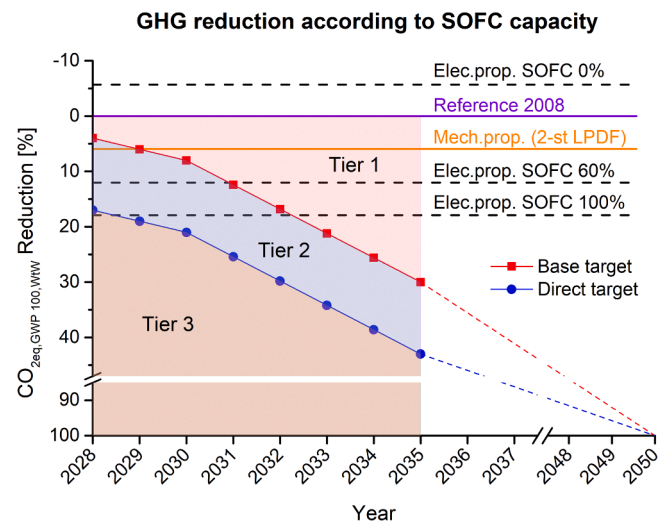


Fig. 12. GHG reduction according to SOFC capacity.

with the degradation rate. As shown in Fig. 9, when the SOFC price is 3660 USD/kW, the total cost of ownership (TCO) of the SOFC hybrid system is better than that of the DF Gen-only system, regardless of whether the degradation rate is $-0.5\%/1000$ h or $-0.2\%/1000$ h. For the $-0.5\%/1000$ h degradation rate, the SOFC price needs to be reduced to around 2400 USD/kW to achieve cost competitiveness of the SOFC hybrid system. However, with a degradation rate of $-0.2\%/1000$ h, the total cost of ownership of a SOFC hybrid system is lower compared to a DF Gen-only system, with an initial SOFC cost of around USD 3500/kW.

3.4. CO₂ reduction according to the SOFC capacity

CO₂ emissions were calculated by applying a 500-hour operational profile to a hybrid system equipped with varying capacities of SOFC. As illustrated in Fig. 10, it is evident that CO₂ emissions from the hybrid system decrease as SOFC capacity increases. However, the rate of CO₂ reduction diminishes once SOFC capacity exceeds a certain threshold. This decline in efficiency is attributed to the operating characteristics of SOFC, which require fuel to maintain the stack temperature even in hot standby mode, where no power is generated. Consequently, when the SOFC installation capacity exceeds the ship's actual power demand, the system may operate at partial load or in standby mode, consuming additional fuel unrelated to power generation and thereby lowering overall system efficiency.

Currently, most large vessels employ mechanical propulsion systems powered by large two-stroke engines. Under such systems, the application of a 500-hour operational profile results in approximately 1600 tons of CO₂ emissions per voyage. This amount is about 90 % of the CO₂ emissions produced by an electric propulsion system using DF Gen alone. The higher CO₂ emissions in the electric propulsion system are due to (1) irreversible energy losses in the power conversion process—such as conversion from the DF Gen to transformers and motors—and (2) the lower fuel efficiency of DF Gen compared to large two-stroke Main Engine.

Implementing a SOFC-based electric propulsion system can result in a reduction in CO₂ emissions compared to mechanical propulsion, starting when 30 % of total electricity demand is produced by SOFC. Even if the system is scaled so that all propulsion power is provided exclusively by SOFC, the maximum reduction in CO₂ emissions compared to mechanical propulsion reaches only about 3 %, as shown in Fig. 10. This limited improvement is primarily due to the already high fuel efficiency of two-stroke Main Engine.

However, when the assessment is expanded to include CO₂-

equivalent emissions ($\text{CO}_{2,\text{eq}}$) based on the 20-year Global Warming Potential (GWP20)—which incorporates the greenhouse effects of methane (CH_4) and nitrous oxide (N_2O)—the environmental benefits of the SOFC system become more pronounced. As shown in Fig. 11, under full SOFC operation, $\text{CO}_{2,\text{eq}20}$ emissions can be reduced by up to 30 % compared to conventional mechanical propulsion systems. This notable decrease highlights the environmentally advantageous potential of SOFC hybrid systems, especially when considering the wider impacts on greenhouse gases.

3.5. Analysis of operating costs considering IMO's GHG reduction targets

As a result of the 83rd session of the International Maritime Organization's (IMO) Marine Environment Protection Committee (MEPC) held in April 2025, a revised medium-term greenhouse gas (GHG) reduction strategy was adopted to support the long-term goal of achieving net-zero emissions by 2050. As depicted in Fig. 12, this strategy outlines annual reduction targets—referred to as the "base target" and "direct target"—relative to the 2008 baseline. Compliance is evaluated using Well-to-Wake (WTW) CO_2 equivalent emissions over a 100-year global warming potential ($\text{CO}_{2,\text{eq}100,\text{WTW}}$), and penalties are imposed when targets are not met.

The penalty is structured in tiers as outlined below.:

- Tier 1: If emissions exceed the base target, a fine of 380 USD/ ton of $\text{CO}_{2,\text{eq}100,\text{WTW}}$ is applied to the excess above the base target, and 100 USD per ton is additionally charged for the shortfall between the base and direct targets.
- Tier 2: If emissions are within the base target but surpass the direct target, a fine of 100 USD/ton of $\text{CO}_{2,\text{eq}100,\text{WTW}}$ is imposed on the difference between current emissions and the direct target.
- Tier 3: If emissions are lower than the specified target, incentives are granted based on the discrepancy between the emissions and the target.

Fig. 12 illustrates estimated CO_2 emissions reductions for a mechanically driven ship with a large two-stroke Main Engine (Low Pressure Dual Fuel), as well as an electric propulsion vessel using different SOFC capacities when operating under a 500-hour load profile. The following important points can be identified:

- LNG-fueled mechanical propulsion vessels are projected to start failing to meet the base target in 2029.
- Vessels with 100 % SOFC electric propulsion can achieve the direct target by 2028, but fall short of this from 2029 onward and are unable to meet even the base target beginning in 2033.

While the hybrid system cannot fully achieve IMO's 2050 decarbonization target when fueled by LNG, it demonstrates potential as a transitional technology. This aligns with Korberg et al (Korberg et al., 2021). and Yuksel et al (Yuksel, 2023)., who highlighted the needs of coupling SOFCs with carbon capture or carbon-neutral fuels to ensure regulatory compliance.

4. Conclusion

The Total Cost of Ownership (TCO) was assessed based on a 20-year operational period for an SOFC hybrid system, comprising a 2 MW SOFC and a 4 MWh ESS. The economic feasibility of this hybrid configuration was analyzed under battery and SOFC stack degradation conditions. For the SOFC system, two degradation scenarios were considered, with efficiency losses of $-0.5 \text{ \%}/1000 \text{ h}$ and $-0.2 \text{ \%}/1000 \text{ h}$, respectively. For the ESS, capacity fade was modeled using a degradation map that considers the aging of both anode, cathode, and electrolyte components. Under the current Tank-to-Wake (TTW) carbon emission standard, which includes only emissions generated from onboard fuel combustion,

it was found that the SOFC hybrid system cannot achieve economic feasibility when the degradation rate is $-0.5 \text{ \%}/1000 \text{ h}$ and the fuel gas price remains below 1000 USD/ton. The economic potential of the SOFC hybrid system is significantly improved when the analysis considers CO_2 emissions across the entire fuel lifecycle, considering the Well-to-Wake (WTW) standard. Under WTW assessment, the system proves cost-effective even under current fuel cell prices, gas prices, and carbon tax rates. However, despite these advantages, it is difficult to achieve the IMO emission reduction target (20–30 % reduction by 2030, complete decarbonization by 2050) with SOFC using fossil fuels.

Hence, it is essential to prioritize the advancement of sustainable technologies in order to integrate SOFC technology into ships in the future. For instance, the integration of carbon capture technology capable of managing anode exhaust gas containing elevated CO_2 concentrations is necessary for the utilization of the SOFC system. Alternatively, by converting to carbon-neutral fuels like ammonia or hydrogen, the SOFC system could serve as a crucial component of a ship propulsion system with zero emissions.

Despite these promising outcomes, several limitations should be acknowledged. Large-scale SOFC systems have not yet been implemented in commercial vessels, and as such, the present analysis relies on modeled performance and extrapolated degradation data rather than empirical long-term evidence. Moreover, the current capital cost of SOFC technology remains considerably higher than that of conventional dual-fuel machinery, constraining its short-term economic viability. These limitations imply that the findings should be interpreted as indicative rather than predictive.

Future research should therefore prioritize pilot-scale demonstrations of SOFC hybrid systems on large commercial vessels to validate operational feasibility and durability under real-world conditions. In parallel, further techno-economic studies are required to examine prospective cost-reduction pathways, fuel supply chain developments, and the integration of carbon-neutral fuels such as hydrogen or ammonia. Finally, coupling SOFC hybrids with carbon capture systems and advanced energy management strategies may provide a more robust pathway toward compliance with IMO's long-term decarbonization targets.

CRedit authorship contribution statement

Suk Won Cha: Funding acquisition, Project administration, Supervision, Writing – review & editing. **Jung Il Lee:** Conceptualization, Formal analysis, Investigation, resources, Writing – original draft. **Daehyuk Kim:** Data curation. **Donghwan Sung:** Methodology. **Hyunjun Yang:** Methodology.

Declaration of Competing 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.

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Data availability

Data will be made available on request.

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