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Onboard Hydrogen Production via Methanol Steam Reforming for Solid Oxide Fuel Cell-Based Hybrid Ship Power Systems

Onur Yuksel · Eduardo Blanco-Davis· Juan Ignacio Ahuir-Torres· G Viknash Shagar· David Hitchmough· Maria Carmela Di Piazza· Marcello Pucci· Nikolaos Tsoulakos· Jin Wang

Abstract This paper evaluates a hybrid ship electrification system featuring a solid oxide fuel cell (SOFC) powered by onboard hydrogen from Methanol Steam Reforming (MSR), complemented by a battery and waste-heat recovery system. Utilising operational data from a Kamsarmax bulk carrier, the model simulates nearly two years of service to quantify energy consumption and lifecycle emissions. This research provides a system-level assessment of the MSR-SOFC pathway against a conventional diesel baseline under representative service conditions. The study highlights the critical trade-offs between operational emission reductions and upstream fuel production impacts, demonstrating the potential of integrated methanol-to-hydrogen systems as a viable decarbonisation solution for the global bulk carrier fleet.

1 Introduction

Although shipping is widely regarded as the most energy-efficient mode of transportation due to its high cargo-carrying capacity, its contribution to air pollution and global climate change remains substantial, largely because of the continued reliance on heavy marine fuels [1]. Maritime transport is responsible for approximately 3% of global greenhouse gas (GHG) emissions, predominantly emitted as carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) [2]. In addition to GHGs, shipping activities generate additional air pollutants, including particulate matter (PM), volatile organic compounds, sulphur oxides (SO_x), and nitrogen oxides (NO_x) [3]. Furthermore to its impact on global warming, the sector poses immediate environmental and public-health challenges, particularly due to the release of harmful pollutants in coastal and port regions, where exposure to the local population is significantly higher [4].

Hybrid power systems integrating hydrogen-fuelled solid oxide fuel cells (SOFCs), battery energy storage, and waste-heat recovery systems (WHRS) offer significant potential to enhance the environmental performance of ship electrification plants. SOFCs enable high electrical efficiency and near-zero pollutant emissions at the point of use, while batteries smooth transient loads and further reduce fuel consumption [5]. Additionally, WHRS technologies can recover high-grade thermal energy from main engine or SOFC exhaust to improve overall system efficiency [6]. Despite these advantages, the widespread adoption of hydrogen-based hybrid configurations is hindered by the challenges associated with hydrogen storage and bunkering, including low volumetric energy density, stringent safety requirements, and limited port infrastructure [7]. To address these limitations, onboard hydrogen production represents a promising pathway to increase system reliability and improve safety by reducing the need for large high-pressure or cryogenic hydrogen storage tanks [8].

Methanol emerges as a particularly suitable feedstock for onboard hydrogen generation due to its favourable

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O. Yuksel · E. Blanco-Davis, J.I, Ahuir-Torres, G.V. Shagar, D. Hitchmough, J. Wang
Liverpool Logistics, Offshore and Marine Research Institute (LOOM) – Liverpool John Moores University
James Pearson Building, Byrom Street,
L3 3AF, Liverpool, UK
e-mail: o.yuksel@ljmu.ac.uk, e.e.blancodavis@ljmu.ac.uk, j.i.ahuirtorres@ljmu.ac.uk, g.v.shagar@ljmu.ac.uk, d.m.hitchmough@ljmu.ac.uk, j.wang@ljmu.ac.uk

M.C. Di Piazza · M. Pucci
National Research Council of Italy (CNR), Institute of Marine Engineering (INM)
via Ugo La Malfa 153,
90146, Palermo, Italy
e-mail: mariacarmela.dipiazza@cnr.it, marcello.pucci@cnr.it

N. Tsoulakos
Laskaridis Shipping Co., Ltd.,
5 Xenias Str. and Ch. Trikoupi,
14562 Athens, Greece
e-mail: tsoulakos@laskaridis.com

physicochemical properties and established handling practices in the maritime sector [9]. It is a liquid at ambient conditions, has a relatively high potential to generate a high hydrogen content, and benefits from simpler storage, transport, and bunkering requirements compared to compressed or liquefied hydrogen [10]. These characteristics make methanol a practical alternative fuel that aligns with existing fuel logistics and safety frameworks. Furthermore, methanol can be reformed efficiently using methanol steam reforming (MSR), a process that can be thermally integrated with SOFC systems by utilising their high-temperature waste heat [11].

SOFCs have been extensively investigated in recent decades for maritime applications, owing to their inherently low environmental impact and their strong potential to support the sector's broader decarbonisation objectives. Early work explored the integration of diesel-fuelled SOFC systems as auxiliary units on naval surface ships [12]. More recent developments have focused on LNG-fuelled hybrid propulsion architectures [13]. In the cruise sector, full-scale evaluations of LNG-SOFC installations indicate that SO_x, NO_x, CO, and PM emissions can be almost eliminated in port, while CO_2 emissions are reduced by approximately 11%, supporting compliance with environmental indices such as the Carbon Intensity Indicator (CII) [14]. Furthermore, complementary studies assessing life-cycle impacts show that ammonia-fuelled SOFC container ships offer clear environmental advantages over diesel-powered counterparts, particularly in terms of GHG and pollutant reduction, positioning SOFC technology as a viable long-term solution for deep-sea shipping decarbonisation [15].

Although SOFC systems have been widely examined for various maritime applications, the literature provides very limited insight into SOFC operation based on MSR for onboard ship power generation. There is a notable absence of research evaluating MSR-fed SOFC plants within the operational profiles, power demands, and integration constraints of bulk carriers. Since bulk carriers constitute one of the most energy-intensive vessel classes, the lack of studies addressing the long-term performance, integration challenges, safety considerations, and feasibility of MSR-SOFC systems for this ship type represents a significant knowledge gap. Consequently, the potential of methanol-reformed SOFC technology to contribute to bulk-carrier electrification and emissions reduction remains insufficiently understood.

Only a limited number of studies have investigated the performance of SOFCs operating on methanol [16]. Compared with natural gas, methanol offers the advantage of a lower reforming temperature, enabling simpler external reforming strategies [17]. Methanol has also been explored as a direct fuel for SOFCs [18], with experiments demonstrating high electrochemical performance and no significant cell degradation [19]. Nevertheless, direct-methanol SOFC configurations remain at an early research stage, and further development is required before practical deployment can be realised [9].

This study develops a model of an SOFC-based hybrid power plant for onboard use on a representative bulk carrier. The system is simulated over 1.96 years, reflecting the remaining dataset after preprocessing. Hydrogen is produced entirely onboard via methanol steam reforming, using grey methanol as the primary fuel. To improve efficiency, an Organic Rankine Cycle (ORC) waste-heat recovery system utilises high-temperature exhaust from the SOFC. Battery stacks accommodate variations in propulsion and hotel loads, stabilising the system against the fuel cell's slow response. Operational inputs, including load profiles and environmental conditions, are based on data from onboard sensors, allowing realistic representation of ship operations. This integrated modelling approach determines and compares the environmental performance of the MSR-SOFC hybrid plant with conventional diesel generator operation for bulk carriers, addressing a gap in existing maritime energy research. A key contribution is the development of a novel energy and emission framework for ships equipped with an MSR-SOFC-Battery-ORC hybrid electrification system. Furthermore, the lifecycle performance of a real ship evaluated using real operating profiles has been evaluated.

2 Method

This study provides contextual background for the research findings and details of the examined system. The case study focuses on the Kamsarmax bulk carrier M/V KASTOR, operated by Laskaridis Shipping Co. Ltd., which was built in 2020 and has a deadweight capacity of 80,996 t and a length of 229 m. The vessel is powered by a HYUNDAI 6S60ME-C8.5 main engine with a maximum output of 9,930 kW and is equipped with three YANMAR 6EY22LW diesel generators, each providing 720 kW of power from Heavy Fuel Oil (HFO).

The methodology begins with thorough data collection and preparation, including preprocessing sensor measurements and operational information such as engine exhaust parameters and fuel/emission characteristics for methanol-based operations. Emission factors and component lifetimes are compiled for realistic modelling.

The next stage determines suitable hybrid system configurations, including hydrogen production methods and MSR subsystems, while defining the capacities of SOFCs and batteries to meet electrification demands. These configurations are evaluated in a hybrid system simulation that dynamically distributes power among the SOFC units, battery stacks, ORC-WHRS and auxiliary generators, responding to fluctuating grid loads. The simulation also calculates methanol and hydrogen consumption based on propulsion demand.

The simulation framework is initialised with a comprehensive set of inputs derived from empirical data and technical specifications. The primary operational input consists of high-fidelity load profiles captured at one-minute intervals from the case study vessel's sensory systems. Technical inputs include the lower heating values of the fuels, carbon intensity factors for various production pathways, and manufacturer-provided efficiency maps for the conventional engine. Furthermore, the model incorporates experimentally validated performance data for the PEMFC stack and the battery energy storage system, including discharge curves and state-of-health degradation parameters.

A dynamic power-split energy management strategy governs the mathematical interconnection between the electrical and thermal subsystems. At any given time step, the total instantaneous power demand is partitioned between the thermal branch, represented by the internal combustion engine, and the electrical branch, comprising the fuel cell and battery pack. This relationship is defined by a power balance where the sum of the power delivered by the engine and the power delivered by the hybrid electrical system must equal the total propulsion and auxiliary demand. The interaction is coordinated by a control logic that prioritises the fuel cell and battery for low-load operations and transient smoothing, while the thermal engine operates as the primary power source during steady-state high-load cruising. This coupling ensures that the thermal efficiency of the engine and the electrochemical efficiency of the fuel cells are optimised simultaneously.

To compute emissions from these power outputs, the framework utilises a well-to-wake lifecycle approach. For the thermal subsystem, the mass flow rate of emissions is determined by multiplying the instantaneous power output of the engine by the specific fuel consumption associated with the specific hydrogen substitution ratio being utilised. This value is then adjusted by an emission factor that accounts for the carbon content and chemical characteristics of the fuel blend. Similarly, for the electrical branch, emissions are calculated based on the energy throughput and the lifecycle carbon intensity of the hydrogen consumed by the fuel cell. The detailed logic and flowcharts explaining the simulation flow can be found in [5,8].

Finally, an environmental analysis quantifies tank-to-wake (TtW) and well-to-tank (WtT) emissions related to methanol use and onboard hydrogen production, enabling a comprehensive assessment of the hybrid methanol-SOFC system's environmental performance. Fig. 1 illustrates the hybrid system configuration in a simplified schematic.

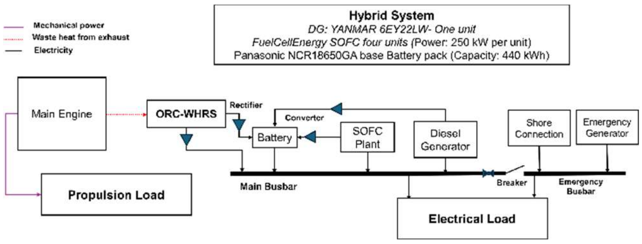

Fig. 1 Simplified scheme of a hybrid electrification system.

The specific fuel consumption values for the conventional engine incorporated into the electrification plant were obtained directly from the manufacturer, with the associated performance curves documented in the authors' previous works. Building upon this foundation, the current configuration also draws from our earlier studies, which focused on optimising the sizing of the fuel cells and batteries to ensure an efficient and balanced power distribution within the hybrid plant [5,8]. Table 1 details the equipment capacities established for the comparative assessment of the hybrid and conventional ship electrification architectures.

Table 1 Equipment capacities in the configurations.

Configuration	DG (kW)	SOFC (kW)	Battery (kWh)	ORC (kW)
DG-HFO	3 × 720	N/A	N/A	N/A
SOFC-Methanol	1 × 720	4 × 250	440	197 Avg

2.1. SOFC

The SOFC unit considered in this study is the 250-kW system produced by FuelCell Energy. Each module operates at a nominal frequency of 60 Hz and achieves a peak electrical efficiency of approximately 65%. The unit generates an exhaust mass flow rate of 1,780 kg/h, with the exhaust temperature reaching 167 °C, providing a valuable source of recoverable thermal energy for integration with onboard MSR system [20]. The hydrogen consumption (HC) of SOFC is calculated employing (1) [21].

$$HC = \frac{t \times P_{SOFC} \times 3600}{LHV \times \eta_{SOFC} \times 1000} \tag{1}$$

The operating time is denoted by t (hours), while the electrical power output of an individual fuel-cell unit is expressed as P_{SOFC} (kW). For hydrogen, a lower heating value (LHV) of 120,000 kJ kg^{-1} is adopted, consistent with values reported in the literature [22]. The degradation of SOFC efficiency, η_{SOFC} taken at 65% initially, is modelled by applying a reduction rate of 0.5% per 1,000 h of operation, following established degradation trends for high-temperature fuel-cell systems [23].

MSR

The equation shown in (2) represents the primary reaction governing MSR. This reforming pathway proceeds at relatively moderate temperatures, typically within the range of 200-300 °C, which makes it well-suited for small-scale and mobile energy systems, including auxiliary power units in maritime applications. Methanol is widely regarded as an efficient hydrogen carrier because it remains a liquid at ambient conditions, facilitating storage, handling, and onboard fuel logistics compared to gaseous hydrogen. MSR relies on the integration of the water–gas shift reaction (3), which converts carbon monoxide (CO) into CO_2 while generating additional hydrogen and improving overall reforming efficiency [24].

$$CH_3OH + H_2O \rightarrow CO_2 + 3H_2 \quad (2)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (3)$$

The analysis calculates that the production of 1 g of hydrogen requires approximately 5.298 g of methanol [25], which in turn leads to the generation of about 7.28 g of CO_2 during the reforming process [26]. Fig. 2 shows the simplified schematic diagram for the MSR process used in the analysis.

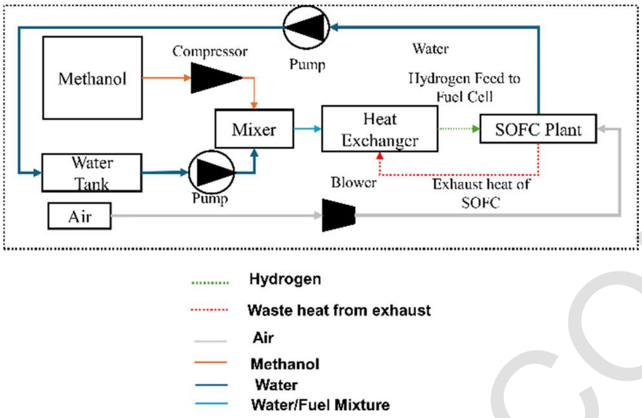

Fig. 2. Simplified scheme of MSR system.

2.2. Battery

A lithium-ion Panasonic NCR18650GA cell with a nominal capacity of 3.45 Ah was adopted for the battery stack due to its high specific energy and favourable performance characteristics for hybrid maritime applications [27]. The battery model employs a constant-current/constant-voltage charging protocol, with a nominal operating voltage of 3.6 V. Voltage decay during discharge is represented by state-of-charge (SoC)-dependent voltage curves from manufacturer specifications [28].

Capacity degradation, expressed as the State of Health (SoH), is incorporated using linear decay relationships that vary according to the applied C-rate. High-rate operation (C-rate > 1) produces a faster decline in capacity (-2.402 mAh per cycle), whereas lower-rate cycling (C-rate ≤ 1) results in a slower degradation rate (-0.3607 mAh per cycle), where both of the operations refer to an initial capacity of 3,412.861 mAh [28].

The Energy Management System determines battery operating states based on the time-evolving SoC, calculated using conventional Coulomb counting. Capacity fade is updated iteratively over the operational timeline, and SoH is computed as the ratio of the degraded capacity to the initial capacity [29]. For grid integration, the DC power from the battery is converted to AC using an SMA Sunny SCS2900 inverter with an efficiency of 98.4% [30].

2.3. ORC-WHRS

The WHRS was implemented as an ORC designed to recover exhaust heat from the main engine when operating above 40% load. The ORC efficiency (η_{orc}) was fixed at 13.2%, consistent with the performance reported by Konur et al [31]. Exhaust gas parameters for the conventional engine were sourced from Yuksel et al. [8]. The exhaust gas outlet temperature (T_{out}) was set to 100 °C. The methodology used to determine the power output of the ORC system is presented in (4) [6].

$$\dot{W}_{WHRS} = \dot{m}_{ex} \times (T_{in} - T_{out}) \times C_p \times \eta_{ORC} \quad (4)$$

Exhaust temperature after steam generation (T_{in}, °C) and the exhaust mass flow rate ($\dot{m}_{ex}$, $kg \cdot s^{-1}$) were interpolated from the main engine data. C_p denotes the specific heat capacity of the exhaust gas at constant pressure. In this analysis, a value of 1.089 $kJ \cdot kg^{-1} \cdot K^{-1}$ was employed, representing the amount of thermal energy required to increase the temperature of one kilogram of exhaust gas by one kelvin [32].

2.4. Environmental Analysis

TtW and WtT emissions for both the conventional and the MSR-integrated SOFC have been calculated using the factors provided in Table 2 [2,33,34].

Table 2 Emissions from conventional and MSR-integrated SOFC

Emission	HFO	Unit	Methanol	Unit
TtW CO_2	3.114	g-CO_2/g-fuel	1.375	g-CO_2/g-fuel
TtW CH_4	0.00005	g-CH_4/g-fuel	0	g-CH_4/g-fuel
TtW N_2O	0.00018	g-N_2O/g-fuel	0	g-N_2O/g-fuel
TtW SO_x	3.23	g/kWh	0	g/kWh
TtW NO_x	15.80	g/kWh	1.44	g/kWh
TtW PM	0.72	g/kWh	0	g/kWh
WtT CO_2e	0.7149	g-CO_2e/g-fuel	0.7299	g-CO_2e/g-fuel
WtT SO_x	0.13	g-WtT/g-TtW	0.16	g/kWh
WtT NO_x	0.07	g-WtT/g-TtW	0.20	g/kWh
WtT PM	0	g-WtT/g-TtW	0	g/kWh

The production of methanol via the Fischer-Tropsch process, commonly referred to as grey methanol, represents the most widely used industrial method for large-scale synthesis [35]. This analysis uses a simplified well-to-wake (WtW) approach, focusing solely on fuel production and operational emissions while excluding the embodied energy and emissions from manufacturing SOFCs and battery systems. Although this allows for consistent comparisons across fuel pathways, it omits significant upstream impacts, especially from batteries, which can contribute an estimated

20-30% to total lifecycle emissions. Using (5), CO_2-equivalent (CO_2e) for global warming potential for 100 years is calculated [2].

$$CO_2e = CO_2 + 265 \times N_2O + 28 \times CH_4 \qquad (5)$$

3 Findings

The comparison of running hours reveals significant variation among the examined technologies. The single SOFC system operates the longest at 17,167 hours, followed by the dual SOFC configuration at 15,066 hours. In contrast, the three-SOFC setup only achieves 1,812 hours, and the four-SOFC system performs even worse at 98 hours. The battery system offers 142 hours of operation, situating it between the three- and four-SOFC configurations. Overall, results show a steep decline in running hours as the number of SOFC units exceeds two, while battery-only operation remains limited.

In 1.96 years of vessel operation, the SOFC system requires 266.25 t of hydrogen, necessitating 1,410.62 t of methanol for hydrogen production via reforming. In comparison, the diesel generator plant consumes 1,823.15 t of HFO to meet the equivalent electrical load over the same period.

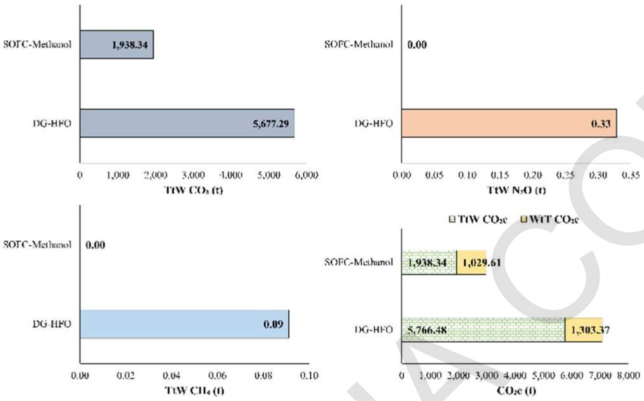

Fig. 3. GHG emission comparison of configurations.

Fig. 3 compares the TtW and WtT greenhouse gas emissions of the conventional diesel generator operating on heavy fuel oil (DG-HFO) with those of the proposed SOFC–methanol hybrid power plant. The results show a significant reduction in TtW CO_2 emissions with the SOFC–methanol configuration, alongside negligible CH_4 and N_2O emissions. Overall, the SOFC-based system achieves a markedly lower CO_2 footprint compared to the DG-HFO baseline, underscoring its potential for onboard emission mitigation.

Emission reductions are substantial when using the SOFC–methanol pathway compared to conventional diesel generator operation. TtW CO_2 emissions decreased by approximately 65.9%, and CH_4 and N_2O emissions are eliminated, resulting in 100% reductions for both. These effects lead to a 66.4% reduction in TtW CO_2e emissions.

On a WtT basis, SOFC–methanol exhibits lower upstream CO_2e emissions due to the energy-intensive nature of methanol production, reflecting a 26.6% decrease compared to HFO. Total WtW emissions show the significant TtW benefits, resulting in an overall 52.3% reduction in lifecycle CO_2e emissions compared to diesel generator operation. This indicates that the SOFC–methanol system provides a considerably lower total emissions profile over the entire energy chain. Fig. 4 illustrates other emissions from the electrification plant configurations.

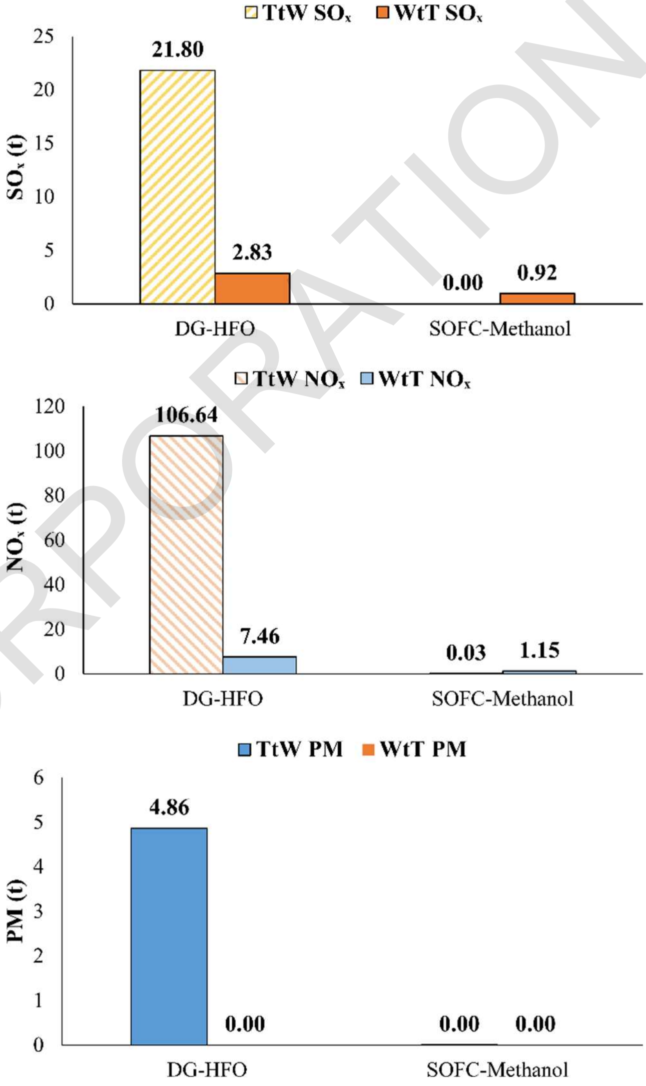

Fig. 4. Other emissions from configurations

The transition from diesel generators to the SOFC plant results in an almost complete elimination of SO_x emissions. TtW SO_x is eliminated and WtT SO_x is decreased by 67% with the SOFC plant with MSR. Similarly, the hybrid configuration reduces the TtW NO_x emissions by 99.97% and WtT NO_x by 84.58%. Additionally, the SOFC plant eliminates the PM emissions.

4 Conclusion

This study developed and evaluated an integrated hybrid ship electrification architecture centred on a solid oxide fuel cell supplied with onboard hydrogen via methanol steam reforming, complemented by battery energy storage and a waste-heat recovery organic Rankine cycle. Using measured operational data from a Kamsarmax bulk carrier, the integrated model captured realistic load dynamics, hydrogen production rates, thermal integration, and emissions across both WtT and TtW boundaries. This approach delivered a consistent, system-level assessment of the MSR-SOFC pathway against a conventional diesel generator baseline under representative service conditions.

The numerical analysis, conducted over a 1.96-year operational horizon, indicates that the SOFC plant consumes 266.25 t of hydrogen produced from 1,410.62 t of methanol, while an equivalent diesel configuration would burn 1,823.15 t of HFO. Compared to the baseline, TtW emissions are significantly reduced, with CO_2 falling by 65.9% and CH_4 and N_2O reduced to zero, achieving a total 66.4% reduction in TtW CO_2e. WtT CO_2e decreases by 26.6% with grey methanol usage and the total WtW CO_2e decreases by 52.3%. Other pollutants are nearly eliminated, with TtW SO_x and PM at zero and NO_x reduced by 99.97%. Upstream SO_x emissions further decrease by 67% and 84.58%, respectively, confirming that the MSR-SOFC pathway significantly reduces lifecycle emissions while meeting marine power demands.

Future research should focus on expanding the fuel pathway analysis to include low-carbon and e-methanol supply chains and incorporating capital costs, operation and maintenance expenses, and degradation-driven maintenance scheduling for techno-economic optimisation. Additionally, it is essential to validate the current model with long-horizon trials and hardware-in-the-loop testing while assessing safety, class compliance, and bunkering logistics for MSR integration. Finally, the framework should be extended to fleet-level dispatch and port-side infrastructure interactions, including shore power and alternative waste-heat recovery options, to ensure a comprehensive understanding of the technology's impact on maritime logistics.

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