Environmental Assessment of a Hybrid Ship Electrification System Integrating Molten Carbonate Fuel Cells, Battery, and Waste Heat Recovery.

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ABSTRACT

This study aims to analyse the integration of a hybrid system, including a Molten Carbonate Fuel Cell (MCFC), battery and an organic Rankine cycle-based waste heat recovery system (WHRS) into marine power distribution through numerical simulations and environmental assessments using sensory data. It contributes to the literature by evaluating the environmental viability of a liquefied natural gas-powered MCFC system as an investment for maritime decarbonisation goals. The data collection was undertaken on a Kamsarmax bulk carrier. The environmental assessment examines the plant's upstream (well-to-tank) and operational (tank-to-wake) emissions. Results indicate that implementing LNG tanks and MCFC has required design modifications to accommodate additional volume and weight. The hybrid MCFC/Battery/WHRS configuration has significantly reduced the marine power distribution plant's equivalent carbon dioxide (CO_2-Eq). Although methane (CH_4) emissions have increased due to LNG usage, non-greenhouse gas emissions have decreased considerably. A rise in combined CH_4 emissions from propulsion and electrification plants has been found. However, the hybrid system has achieved a considerable reduction in CO_2-Eq.

Keywords: Hybrid power system, fuel cell, maritime decarbonization, emissions, ship electrification

1. INTRODUCTION

Maritime transportation has been responsible for a great deal of air pollution due to the increasing usage of fossil fuels and its utilisation share in transportation [1, 2]. Marine diesel engines (MDE) in shipping have produced 3 % of global greenhouses (GHGs) that increase the risk of global warming while also yielding other health hazards [3-5]. To decrease the environmental damage due to shipping activities, the International Maritime Organization (IMO) has entered emission reduction objectives into force and revised them in July 2023 [6]. The updated decarbonisation targets aim to reduce emissions by 20% before 2030 and 70% by 2040 relative to 2008. Finally, there is an intention to achieve net-zero emissions by 2050 [7]. Energy efficiency improvements can be achieved through conventional measures such as engine power limitation, alternative energy sources or speed optimization [8, 9].

Molten Carbonate Fuel Cells (MCFC) have been investigated as an option in hybrid or stand-alone applications for marine propulsion and power distribution units focusing on large commercial vessels. Dimopoulos et al. [10] conducted an exergy analysis on MCFC and WHRS while optimising the configurations. Optimising the simple MCFC system has improved exergy efficiency. In the combined cycle MCFC, heat recovery boosted power by 40%and achieved a 45% relative increase in efficiency. İnal and Denİz [11]presented a case study reducing emissions based on MCFC usage on a chemical tanker's propulsion unit., Baccioli et al. [12] created an MCFC-MDE hybrid model to gauge the efficiency. Compared to the sole MDE-utilised conventional scenario, efficiency improvement was obtained. Korkmaz et al. [13] performed a benchmarking of different FC types and found that a MCFC/battery combination led to a 49.75% operational CO_2 reduction. Yuksel and Bayraktar [14] built an analysis considering MCFC plants in propulsion and auxiliary systems and obtained a 51.7% CO_2 decrease.

This study's motive is to provide an analysis of hybrid MCFC/Battery/WHRS integration to the marine power distribution plant through numerical simulation, and environmental performance assessments using sensory data for more precise data analysis.

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2. MATERIALS AND METHODS

This section explains the framework and mathematical background of the methodology used while highlighting the specifications of the case study elements. Data collection included power output, engine speed, fuel consumption of main and auxiliary engines and vessel-specific parameters such as speed, draft, and deadweight over 1.96 years. The study's industry partner provided the ADLM-sourced data and noon reports from the Kamsarmax bulk carrier, Laskaridis Shipping Co. Ltd. The data was analysed and an MCFC/Battery/WHRS hybrid system was designed to meet the vessel's power demand. A numerical model was developed to estimate the LNG consumption of the MCFC and benchmark its emission reduction against conventional diesel engines. The algorithm calculates exhaust flow and temperature based on engine power, followed by power generation from the WHRS. It then evaluates the main and auxiliary engines' utilization times, fuel consumption, and emissions. Subsequently, LNG consumption and emissions from the MCFC system are computed. Results are logged, converted into data frames, and exported to spreadsheets for analysis.

2.1. Case Study

The vessel selected for the case study is a Kamsarmax bulk carrier, the M/V KASTOR. Constructed in 2020, the ship has a deadweight (DWT) of 80,996 tons and a length overall (LOA) of 229 meters. Its propulsion system comprises of a HYUNDAI 6S60ME-C8.5 engine, capable of delivering a maximum power output of 9,930 kW. Additionally, the vessel is equipped with an electrification plant consisting of three YANMAR 6EY22LW diesel generators (DGs), each providing a terminal power capacity of 720 kW. Figure 1 indicates a simplified schematic of the proposed hybrid marine power distribution system, which integrates an MCFC, battery, and WHRS. The diagram also includes the LNG cracking process based on water-gas shift reactions.

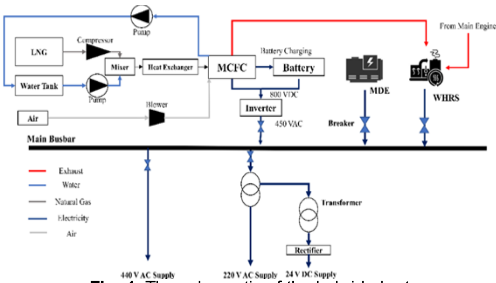

Fig. 1. The schematic of the hybrid plant

The conventional power plant consists of three equivalent DGs with a total output of 2,160 kW. In contrast, the hybrid plant features a single MCFC unit with a power output of 1,400 kW and a battery with a capacity of 40 kWh to accommodate instantaneous increases in power demand. The WHRS can generate up to 200 kW of electrical power, primarily utilising waste heat from the main engine's exhaust, with supplemental heat from the MCFC when necessary. The MCFC unit has an LNG reforming system for hydrogen production. One DG is maintained to ensure emergency reserve. The battery cell for assembling the stack utilisszed in the hybrid configuration to support the SureSource 1500 MCFC system is the Panasonic NCR18650GA, featuring a capacity of 3.45 Ah and a nominal voltage of 3.6V. The specifications of the MCFC unit employed in the system are presented in Table 1. LNG consumption and emissions of MCFC system have been computed from the coefficients given in Table 1 depending on the energy generated.

Table 1. MCFC specifications[15].

Parameter	Value	Unit
Electric Power Output	1400	kW
Electrical Efficiency	47%±2%	-
LNG Consumption	615.12	m³/h
NO_x	0.0045	kg/MWh
CO_2	444.5	kg/MWh
PM	9.07*106	kg/MWh
SOx	0.000045	kg/MWh
Weight	48.53	t
Length/Width/Diameter	16.98/3.88/6.09	m

2.2. Modelling Background

The WHRS utilises an Organic Rankine Cycle (ORC) to generate electricity from the exhaust waste heat. The exhaust flow rates and temperatures of the main engine after the turbine exit data have been gathered from the main engine (ME) manufacturer's datasheet [16]. The ORC model is based on the models developed by Konur et al. [17]. Equation 1 indicates the calculation of WHRS power generation $\dot{W}_{WHRS}$) in kW [18].

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$$\dot{W}_{WHRS}\ (kW) = \dot{m}_{ex} \times \left(T_{in,\,ex} - T_{out,\,ex}\right) \times C_{p,\,ex} \times \eta_{ORC}. \tag{1}$$

where $\dot{m}_{ex}$ represents the exhaust mass flow rate in kg/s, $T_{in,\,ex}$ denotes the inlet temperature of the exhaust (after the exhaust boiler), and $T_{out,\,ex}$ is the outlet temperature from the ORC, which is set at 100°C. The specific heat capacity at constant pressure, $C_{p,\,ex}$, is the amount of thermal energy the exhaust gas emits or absorbs when its temperature changes, assuming constant pressure, and is taken to be 1.089 kJ/kg [19]. The efficiency of ORC (η_{ORC}) is 13.2% [17].

The algorithm calculates the required engine power and the number of active generators for each time interval (t = 1 minute). In the simulation, the load and power of each generator were determined, and their specific fuel consumption was obtained by interpolating the curve provided by the manufacturer. The load distribution has been established using the model presented by Yuksel and Koseoglu [4]. The operational emissions (OE) in g of the MCFC and MDEs have been calculated employing the operational emission factors (OEF) given in Table 1 (for MCFC) and Table 2 (for heavy fuel oil (HFO)) [14]. The OEF and upstream emission factors (UEF)for HFO and the UEF for LNG are presented in Table 2.

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Table 2. Emissions of the main propulsion plant [20-22].

Emission Factor	CO_2	N_2O (g/kWh)	CH_4 (g/kWh)	NO_x	SO_x	PM	VOC
LNG - UEF	0.131	0.004	1.718	0.007	0.158	0	0
HFO - UEF	0.147	0.004	0.879	0.010	0.102	0.022	0
HFO – OEF	3.114	0.00015	0.00006	0.903	0.025	0.00278	0.004

The LNG – UEF SOx coefficients, nitrous oxide (N_2O), and methane (CH_4) units are in g/kWh, while others are in g-UE/g-OE. Equation 2 indicates the calculation of upstream emissions (UE) depending on the unit of the UEF [1].

$$UE(g) = \sum P\ (kW) \times t(h) \times UEF\ \left(\frac{g}{kWh}\right) \text{ or } UE(g) = UEF\ \left(\frac{g\text{-}UE}{g\text{-}OE}\right) \times OE\ (g) \qquad (2)$$

The power output of the electrification plant, in general, is depicted as P in Equation 2. The equivalent CO_2 (CO_2-Eq) considering the global warming potential for 100 years has been calculated using the IMO Life Cycle Assessment Guideline for alternative fuels [23]. The CH_4 slip in MCFCs has been insignificant, unlike dual-fuel engines, and can be prevented by smart engineering applications [24].

3. FINDINGS

The analysis spans 17,167 operating hours (1.96 years), covering the entire operation period. Fuel consumption was measured at 8,851.62 t for the ME and 1,823.15 t for the DGs, while the MCFC LC required 3,491.13 t to meet the same power demand. Accordingly, the LNG capacity of the hybrid plant was set at 655.95 m³, with a reduced HFO capacity for the MDEs calculated at 2,425.52 m3. The marine power distribution plant delivered 6,749.27 MWh over 1.96 years, averaging 3,443.93 MWh annually. Table 3 summarises emissions from the main propulsion plant during this period.

Table 3. Emissions of the main propulsion plant

Pollutant	OE	UE	Total
CO_2	27,563.96	4,051.90	31,615.86
N_2O	1.33	0.19	1.52
CH_4	0.53	41.97	42.50
CO_2-Eq	27,930.68	5,277.62	33,208.30
NO_x	7,993.02	79.93	8,072.95
SO_x	221.29	22.57	243.86
PM	24.61	0.54	25.15
VOC	27.26	0.00	27.26

The propulsion plant has emitted 33,208.3 tons of CO_2-eq over 1.96 years, resulting in an average annual emission of 16,943 tons of CO_2-eq. NOx emissions have been the second highest, averaging 4,118.85 tons (t) annually. Fig. 2 illustrates the operational and upstream emissions for conventional and hybrid marine power distribution plants. Fig. 2 shows that the conventional plant emitted much more CO_2 overall than the hybrid plant. Notably, the hybrid plant eliminated operational N_2O emissions, but the upstream component remains the same. Likewise, the hybrid plant eliminated operational CH_4 emissions.

Figure 3 indicates the non-GHG emissions from the hybrid and conventional plants. The hybrid plant is shown to eradicate overall NOx emissions. Operational SOx emissions were effectively eliminated. LNG usage has been proven to reduce SOx upstream emissions substantially.

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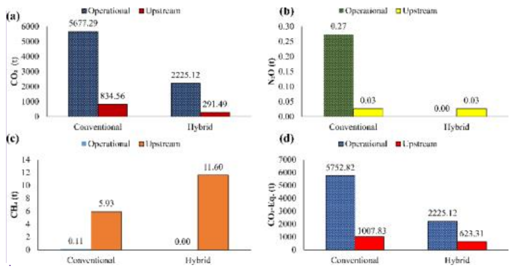

Fig. 2. GHG emissions of the ship electrification plants: (a) CO_2, (b) N_2O, (c) CH_4, and (d) CO_2-Eq.

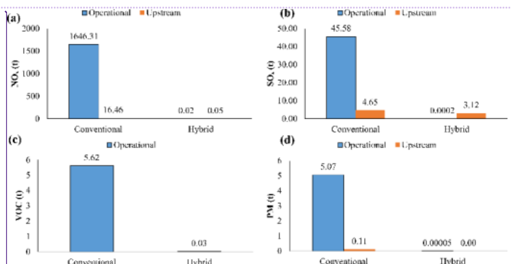

Fig. 3. Other emissions of the ship electrification plants: (a) NOx, (b) SOx, (c) VOC, and (d) PM.

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LNG avoids upstream PM emissions from HFO. Additionally, the hybrid unit heavily reduces operational PM and operational VOC emissions.

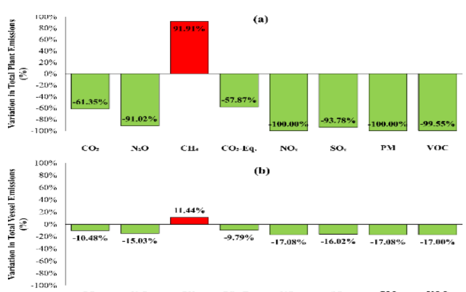

Fig. 4. Emission variations of the hybrid system in (a) sole electrification plant and (b) overall vessel emissions including propulsion unit in comparison with that using the conventional system.

Figure 4 summarizes total emissions from the electrification plant and combined emissions from the power and propulsion units, highlighting significant reductions in NOx, SOx, PM, and VOC emissions achieved through the hybrid configuration. The total emissions of the ship's electricity generation plant have been reduced, except for CH_4, which increased significantly, as shown in Figure 4 (a). The overall CO_2 reduction of the plant is considerable, yielding a slight decrease in the overall emissions of the propulsion and electrification plants. Despite the small CH_4 increment in combined emissions, the hybrid plant achieved a CO_2-Eq decrease while other emissions have been reduced drastically.

4. CONCLUSIONS

This study evaluated the integration of an MCFC/Battery/WHRS hybrid system into a marine electrification plant using a mathematical model supported by sensor-based data from a Kamsarmax bulk carrier recorded over a period of nearly two years. Environmental performance was assessed, including a future cost projection scenario, to examine the viability of an LNG-powered MCFC system as an alternative solution to decarbonize the maritime sector. The analysis incorporated upstream and operational emissions. Key findings include:

- The MCFC/Battery/WHRS hybrid system reduced CO_2-Eq emissions from the marine power distribution plant by 57.87%.
- CH_4 emissions increased due to LNG usage, but non-GHG emissions were significantly reduced.
- Despite an 11.44% rise in combined CH_4 emissions from propulsion and electrification plants, the hybrid system achieved a 9.79% reduction in overall CO_2-Eq emissions.

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