



# Economic Assessment of MCFC and WHRS Integration for Ship Electrification: A Bulk Carrier Case Study

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**Abstract.** This study evaluates the economic viability of integrating a Molten Carbonate Fuel Cell (MCFC), battery and Organic Rankine Cycle-based Waste Heat Recovery System (WHRS) into a marine power distribution system using data from a Kamsarmax bulk carrier of Laskaridis Shipping Co. LTD. A future-oriented economic analysis compared the hybrid system with conventional marine diesel engine (MDE) power plants. The study considered key cost components such as installation, operation, maintenance, fuel, and carbon tax costs over a 20-year lifespan. The results indicate that, in 2024, the MDE power plant is more cost-effective, with a Levelized Cost of Energy (LCOE) of \$230.87/MWh compared to \$422.05/MWh for the hybrid plant. However, by 2030, the gap will diminish due to anticipated declines in MCFC costs and rising carbon taxes, making the hybrid system competitive. Projections for 2050 demonstrate a reversal, with the hybrid plant achieving an LCOE of \$243.98/MWh in the low-price scenario, which is 51% lower than the conventional system under the same conditions. The high initial cost of the MCFC, driven by equipment expenses and renewal requirements, is identified as the primary economic barrier. Nonetheless, advancements in MCFC technology and escalating regulatory pressures on emissions are expected to shift the financial landscape, favouring hybrid configurations. This study highlights the long-term potential of hybrid systems as a sustainable and economically viable solution for maritime decarbonisation, providing valuable insights for policymakers and stakeholders in the shipping industry.

**Keywords:** Liquefied Natural Gas (LNG) · Molten Carbonate Fuel Cells · Waste Heat Recovery System · Organic Rankine Cycle · Economic Analysis · Ship Electrification Plant

## 1 Introduction

Maritime transportation has been a source of emissions for decades due to its heavy reliance on fossil fuels. The maritime industry produces about 3% of the world's greenhouse gas emissions linked to global warming. Additionally, various other forms of emissions, such as sulphur oxides (SO<sub>x</sub>), nitrogen oxides (NO<sub>x</sub>), volatile organic compounds (VOC) and particulate matter (PM), are hazardous to human health [1, 2]. The International Maritime Organization (IMO) has introduced emission targets which have come into force. These include updated decarbonisation targets that aim to cut emissions by 70% before 2040 relative to 2008 levels and achieve net zero emissions by 2050 [3]. Energy efficiency plays a key role in decarbonisation. Technologies such as engine power management, air lubrication, hull cleaning, and the application of energy-saving devices can play a massive role in achieving net-zero emissions. Alternative energy sources such as batteries, fuel cells, photovoltaic panels, and a waste heat recovery system also reduce the emissions of vessels [4].

Despite high initial costs, the economic outlook for integrating alternative energy sources onto the shipboard power system appears favourable. In this regard, the Molten Carbon Fuel Cell (MCFC) is noteworthy and would be the type of fuel cell investigated in the following sections. The hydrogen fuel is supplied by Liquefied Natural Gas (LNG) through a steam-methane reforming process [5]. LNG has the advantage of being almost sulphur-free, resulting in near-elimination of SO<sub>x</sub> emissions. LNG has the benefit of having existing logistical networks and rapidly developing bunkering infrastructure [6]. Since LNG-powered ships have operated since the 1990s, retrofitting possibilities for fuel cells could be more palatable for ship owners. The high power capacity of the MCFC introduces the possibility of its being used in a more extensive variety of ships [7]. A larger fuel cell capacity also reduces the size and, hence, the cost of other energy sources, such as batteries [8]. Recent developments in cell and stack efficiency of the fuel cells have brought their capital cost down [9]. Hydrogen fuel consumption remains a significant part of the operation of a fuel cell [10]. Therefore, a mix of other energy systems that are relatively low cost, such as the Waste Heat Recovery System (WHRS), must be integrated into the network to make the cost of onboard energy more economical and enable diverse options for ship electrification [11].

It has been illustrated that the energy cost could be reduced by about 25% when the supply from fuel cells with battery storage is combined with output from a photovoltaic source compared to a case without the same. In calculating the lifecycle cost of the fuel cell, other costs such as the replacement costs, operation & maintenance costs and repair costs must be considered in addition to the purchase and installation costs. Generally, these costs are much higher for fuel cells than for solar power or battery systems [12]. The levelized cost of electricity (LCOE) for the MCFC system can range from \$97.20 to \$126.00 per MWh, contingent upon the current density of the fuel cell configuration [13]. However, the decreasing trend in capital costs of fuel cells and increasing hydrogen costs indicate a continued drop in the cost of electricity produced from hybrid fuel cell systems [14].

## 2 System Configuration and Method of Analysis

### 2.1 Description of the System

Marine diesel generators power the Kamsarmax bulk carrier used for this case study. Table 1 provides a brief overview of the ship's specifications.

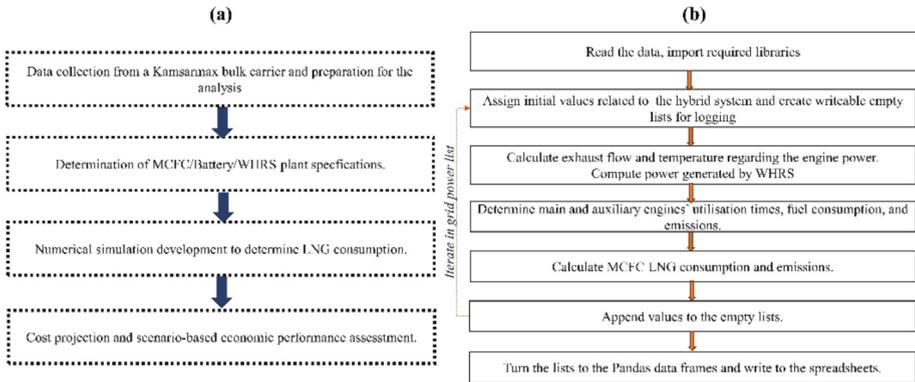
**Table 1.** Overview of the ship's specifications.

Parameter	Value	Unit
Date of Build	2020	-
Gross Tonnage	43,993	-
Net Tonnage	27,293	-
Deadweight	80,996	t
Length Overall	229	m
Breadth	32.26	m
Draught	14.45	m
Freeboard	5.629	m
ME Power	9,930	kW
DGs	3 × 720	kW
Frequency	60	Hz
Vessel Speed	14.3	kt
Fuel Capacity	2738.3	m <sup>3</sup>
Date of Build	2020	-

It is worth noting that this work focusses only the economic aspect of the system. The MCFC system in analysis is the SureSource 1500, which delivers a power output of 1.4 MW and achieves a peak efficiency of 47%. These units are commercially available products, thereby facilitating their theoretical integration into existing energy systems. The proposed system integrates a MCFC supplied by hydrogen obtained through the steam-methane reforming process. The integrated LNG reforming system utilises the heat generated within the MCFC unit to produce hydrogen. The exhaust temperature of the MCFC, approximately 370 °C, is utilised in this process, resulting in the emission of 444.521 kg of carbon dioxide per megawatt-hour of generated power [15].

A Waste Heat Recovery System (WHRS) up to 200 kW of power output has also been added to supplement the energy requirements, thus, reducing the energy demand from the marine diesel generators. An Organic Rankine Cycle (ORC) design, achieving an efficiency of 13.2% [16], is implemented within the WHRS to harness the waste heat produced by the main engine exhaust during navigation with supplemental heat from the MCFC when necessary. The main engine load-dependent exhaust mass flow rate and temperatures are employed to calculate the power output of the WHRS [4]. The

methodology and the algorithm for the calculation employed in the analysis are shown in Fig. 1.



**Fig. 1.** (a) Methodology flowchart. (b) Algorithm scheme of the hybrid plant model.

In Fig. 1(a) the process begins with data collection from a bulk carrier, focusing on its specifications for analysis. Next, the study determines the key parameters of the MCFC and evaluates the corresponding plant specifications. Subsequently, a numerical simulation is developed to assess the LNG consumption accurately. Finally, the study conducts a cost projection and scenario-based economic assessment to evaluate the financial implications.

Figure 1(b) indicates the simulation steps, commencing with importing necessary libraries and data reading. Initial values of the hybrid system are assigned, while empty lists are created for efficient data logging. Subsequently, calculations are conducted to determine power generation and temperature requirements, specifically targeting the energy output from the WHRS. The simulation then determines fuel consumption, emissions, and operational timelines related to ship electrification equipment. The final step involves appending the calculated data to the empty lists and organizing the data frames for subsequent analysis.

Figure 2 illustrates a schematic of the proposed hybrid marine power system. Due to the MCFC, the WHRS, and battery storage, the number of marine diesel generators has been reduced from three to one.

The conventional configuration consists of three marine diesel engines (MDEs), each providing a power output of 720 kW. In this study, two MDEs are replaced by an integrated MCFC/battery/WHRS system to effectively address the vessel's electrical load, while one MDE is retained as a backup.

The hybrid plant features a single MCFC unit with a power output of 1,400 kW, complemented by a battery with a capacity of 40 kWh to accommodate instantaneous increases in power demand. The battery is intended to address the limitations of the MCFC in terms of load following capabilities. Given that MCFCs respond slowly to load changes, the battery plays a critical role in managing transient demand fluctuations. The battery cell utilised in the hybrid configuration to support the SureSource 1500

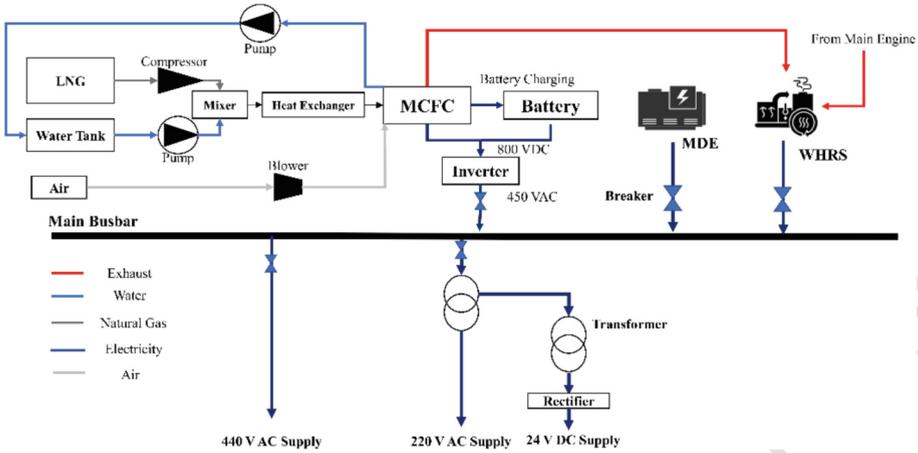


Fig. 2. Hybrid marine power system.

MCFC system is the Panasonic NCR18650GA, which has a capacity of 3.45 Ah and a nominal voltage of 3.6 V.

The air is supplied to the cathode side of the MCFC via a blower. The system also pumps produced water to a storage tank, which is utilised for mixing with LNG. This process, facilitated by a mixer and heat exchanger, induces a water gas shift reaction that generates hydrogen to use in the MCFC plant [5].

### 2.2 Economic Analysis

The economic performance of the cases has been evaluated using the LCOE, which is the primary tool for assessing unit costs at the plant level for various baseload technologies over their operational lifetimes [17]. Equation 1 shows how the LCOE is calculated [18].

$$LCOE \left( \frac{\$}{kWh} \right) = \frac{\sum_{t=1}^n \frac{(C_{plant} + C_{fuel} + C_c + C_{o\&m}) (\$)}{(1+r)^t}}{\sum_{LT=1}^n \frac{P(kW) \times t(h)}{(1+r)^n}} \quad (1)$$

The installation expenses are represented as  $C_{plant}$ , fuel expenditures as  $C_{fuel}$ , carbon tax as  $C_c$ , and the costs associated with operation and maintenance, or capital expenditures are denoted as  $C_{o\&m}$ . A discount rate ( $r$ ) of 10% has been used, and the plant’s operational lifespan ( $LT$ ) is set at 20 years [18]. Table 2 demonstrates the  $LT$ ,  $C_{plant}$ , and  $C_{o\&m}$ .

The calculation of  $C_{o\&m}$  was conducted by multiplying the ratios in the  $C_{o\&m}$  column provided in Table 4 with the values of  $C_{plant}$ . The analysis has been conducted using United States Dollars (\$), with an exchange rate of 1.11 for Euro (€) to \$ on 17 September 2024. Historical prices have been adjusted by applying the relevant year’s exchange rate, and the most recent Chemical Engineering Plant Cost Index (CEPCI) reported at 800.3 for February 2024 [21].  $C_{fuel}$  and  $C_c$  have been evaluated by cost projection cases based on low, medium, and high for 2024, 2030, and 2050. Table 3 indicates  $C_{fuel}$  and  $C_c$  regarding these scenarios.

**Table 2.**  $C_{\text{plant}}$ ,  $C_{\text{o\&m}}$  and LT of scenarios.

Equipment	$C_{\text{plant}}$ 2024	$C_{\text{plant}}$ 2030	$C_{\text{plant}}$ 2050	$C_{\text{o\&m}}$	Unit	LT	Reference
MCFC	7,256,889	6,269,952	2,980,162	1.5%	\$/unit	40000 h	[7, 19]
LNG Storage	2,000	1,800	1,600	1.5%	\$/m <sup>3</sup>	25 years	[20]
HFO Storage	1497.10	1497.10	1497.10	1%	\$/m <sup>3</sup>	25 years	[14]
LNG Transfer	836.20	836.20	836.20	4%	\$/t	10 years	[14, 21]
Organic Rankine Cycle (ORC)	1,348,579	1,348,579	1, 1,348,579	1.5%	\$	20 years	[11]
Battery	11.36	11.36	11.36	1%	\$/cell	10 years	[22, 23]
AE Installation Cost	628,651	628,651	628,651	1.5%	\$	25 years	[24]

**Table 3.**  $C_{\text{fuel}}$  and  $C_C$  in the analysis (the unit is \$/t).

$C_{\text{fuel}}$ LNG	Low	Medium	High	Unit	Reference
2024	671	N/A	N/A	\$/t-fuel	[25]
2030	588.84	627.10	694.50	\$/t-fuel	[24, 26, 27]
2050	314.98	480.76	770.89	\$/t-fuel	[24, 26, 27]
$C_{\text{fuel}}$ HFO	Low	Medium	High		
2024	574	N/A	N/A	\$/t-fuel	[24, 26, 27]
2030	635.99	656.66	673.88	\$/t-fuel	[24, 26, 27]
2050	842.63	932.18	1006.8	\$/t-fuel	[24, 26, 27]
$C_C$	Low	Medium	High		
2024	76.74	N/A	N/A	\$/t-CO <sub>2</sub>	[28, 29]
2030	94.82	135	250	\$/t-CO <sub>2</sub>	[29, 30]
2050	155.17	674.00	1285.00	\$/t-CO <sub>2</sub>	[29, 30]

The  $C_{\text{fuel}}$  values for 2024 were gathered from ShipandBunker [25] on 14 September 2024. For the 2030 and 2050 scenarios, the low case assumes slow increments or steep reductions, the medium case reflects moderate rises or falls, and the high case involves rapid increases or decreases. Based on the literature data, this framework has been similarly applied to carbon tax prices aligned with the respective fuel price scenarios.

### 3 Results

The values  $C_{\text{plant}}$  and  $C_{\text{o\&m}}$  for hybrid and conventional plants in 2024, 2030, and 2050 have been calculated and shown in Tables 4 and 5, respectively.

**Table 4.** Total  $C_{\text{plant}}$  in the analysis (units are \$).

Lifetime $C_{\text{plant}}$	MCFC plant			MDE plant		
	2024	2030	2050	2024	2030	2050
Fuel Cell	58,055,111	50,159,616	23,841,299	0	0	0
Battery	74,840	74,840	74,840	0	0	0
LNG Storage	1,311,897	1,180,707	1,049,517	0	0	0
LNG Transfer	244,868	244,868	244,868	0	0	0
HFO Storage	233,386	233,386	233,386	700,157	700,157	700,157
ORC	1,348,579	1,348,579	1,348,579	0	0	0
MDE	628,651	628,651	628,651	1,885,952	1,885,952	1,885,952
<b>Total <math>C_{\text{plant}}</math></b>	<b>61,897,331</b>	<b>53,870,646</b>	<b>27,421,139</b>	<b>2,586,110</b>	<b>2,586,110</b>	<b>2,586,110</b>

**Table 5.** Annual  $C_{\text{o\&m}}$  in the analysis (units are \$).

	MCFC plant			MDE plant		
Fuel Cell	108,853	94,049	44,702	0	0	0
Battery	748	748	748	0	0	0
LNG Storage	19,678	17,711	15,743	0	0	0
LNG Transfer	9,795	9,795	9,795	0	0	0
HFO Storage	2,334	2,334	2,334	10,502	10,502	10,502
ORC	20,229	20,229	20,229	0	0	0
MDE	9,430	9,430	9,430	28,289	28,289	28,289
<b>Total <math>C_{\text{o\&amp;m}}</math></b>	<b>171,067</b>	<b>154,295</b>	<b>102,981</b>	<b>38,792</b>	<b>38,792</b>	<b>38,792</b>
Fuel Cell	108,853	94,049	44,702	0	0	0

Considering MCFC's LT and utilisation hours at least eight times during its life period, the unit must be replaced or overhauled heavily, which has increased the estimated cost remarkably. The battery packs have not been actively involved in the operation; however, it is assumed that they will be replaced every ten years. Implementing an MCFC/Battery/WJHRS hybrid plant has been 23.93 times more expensive than the MDE plant in 2024. Assuming the installation cost reduction taken in the study, in 2030,

this value is 20.83, and in 2050, 10.60 when the costs of MDEs are taken unchanged. Figure 3 illustrates the LCOEs of conventional and hybrid plants regarding fuel and carbon projections based on the low, medium, and high scenarios.

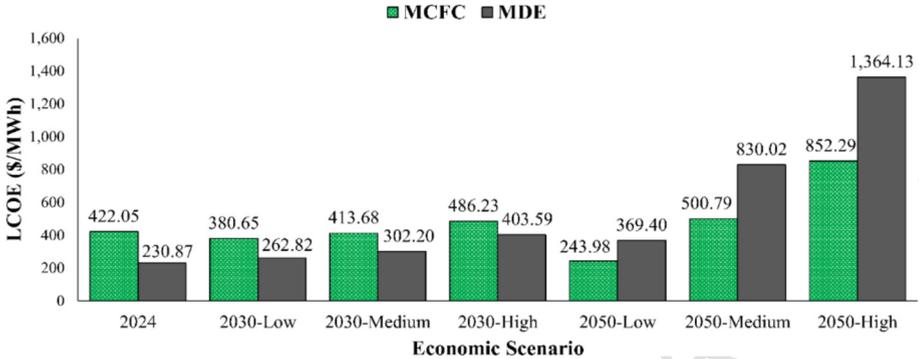


Fig. 3. LCOE variations in (a) MCFC and (b) MDE plant.

The LCOE of the base case in 2024 has been at 230.87 \$/MWh, while the proposed hybrid plant has achieved 422.05 \$/MWh, 1.83 times higher than the conventional scenario's. Starting in 2030, the difference between MCFC and MDE configurations has shrunk. In the 2030 low-case scenario, the hybrid plant has an LCOE of 380.65 \$/MWh, 1.45 times higher than conventional plant's. In medium and high scenarios, with the increasing carbon and HFO prices, this value has decreased to 1.37 and 1.21, respectively.

In 2050 projections, the situation has been reversed, while the conventional HFO-utilised plant has been expected to be less viable in terms of economic performance due to climbing carbon tax prices. The MCFC plant has achieved an LCOE of 243.98 \$/MWh in the 2050 low scenario, which is as low as the 2024 conventional plant's LCOE. In the same scenario, the MDE plant has 1.51 times higher LCOE. In 2050, the medium and high cases show significantly increased carbon and fuel prices; therefore, both plants' LCOEs have increased drastically. Since carbon emissions have been emitted much more in conventional power distribution plants, their LCOE has been 1.65 and 1.59 times higher than that of the MCFC unit in medium and high projection cases, respectively.

The trends elucidated in the results are consistent with existing literature [7, 26, 31], which forecasts a decline in costs associated with renewable technologies and an increasing viability of low-carbon systems in response to rising carbon pricing [29, 32]. These observations underscore the potential for hybrid systems to emerge as economically competitive solutions in the transitioning energy landscape. Furthermore, the alignment of the study's outcomes with established literature reinforces the validity and robustness of the analysis.

## 4 Conclusion

This study analysed the integration of an MCFC/Battery/WHRS hybrid system into a marine electrification plant through a mathematical model. Economic performance assessments were conducted using sensor-based data from a Kamsarmax bulk carrier

over nearly two years. The study presented a novel future cost projection scenario for financial analysis, evaluating the viability of an LNG-powered MCFC system as an investment for maritime decarbonisation. The analysis considered investment, fuel, and carbon tax costs. One key finding of this study is that the MCFC units in the electrification unit are the most significant cost contributors. This is mainly due to their high initial investment and the need for periodic renewals.

Also, the MDE plant was economically more feasible in 2024. However, by 2030, the MCFC would become competitively priced and by 2050, it would be a more viable option. The limitation of the study is that the equipment costs that were unavailable for future projections were assumed to remain constant in the economic model. Further financial analysis based on other types of fuel cells has been planned. A battery storage system controlled by a charging and discharging system based on energy demand and supply of the hybrid marine power system is another avenue of work that can be explored. The researchers believe that the contribution of this work can be of reasonable and useful assistance to researchers and ship owners when they study the possibility of retrofitting their vessels with alternative energy sources.

**Acknowledgements.** The authors would like to acknowledge the financial support for Retrofit Solutions to Achieve 55% GHG Reduction by 2030 (grant number: 10064483) from UKRI and from EU (grant number: Horizon Europe 101096068).

**Disclaimer.** This paper is the opinion of the authors and does not necessarily represent the belief and policy of their employers.

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