POLISH MARITIME RESEARCH 3 (119) 2023 Vol. 30; pp. 59-70
10.2478/pomr-2023-0039

ECONOMIC ANALYSIS AND THE EEXI REDUCTION POTENTIAL OF PARALLEL HYBRID DUAL-FUEL ENGINE–FUEL CELL PROPULSION SYSTEMS FOR LNG CARRIERS

Nader R. Ammar
[a] Department of Marine Engineering, Faculty of Maritime Studies, King Abdulaziz University, Jeddah, Saudi Arabia
[b] Department of Naval Architecture and Marine Engineering, Faculty of Engineering, Alexandria University, Egypt
Majid Almas,
Qusai Nahas
Department of Marine Engineering, Faculty of Maritime Studies, King Abdulaziz University, Jeddah, Saudi Arabia

---

* Corresponding author: *nammar@kau.edu.sa (Nader R. Ammar)*

ABSTRACT

One potential solution for reducing carbon dioxide emissions from ships and meeting the Energy Efficiency Existing Ship Index (EEXI) requirements is to use a hybrid propulsion system that combines liquid hydrogen and liquefied natural gas fuels. To improve energy efficiency for diesel-electric dual-fuel ship propulsion systems, an engine power limitation system can also be used. This paper examines the potential use of these systems with regard to several factors, including compliance with EEXI standards set by the International Maritime Organization, fuel ratio optimisation, installation requirements, and economic feasibility. As a case study, an LNG carrier is analysed, with dual-fuel diesel-electric and two hybrid systems adjusted to meet IMO-EEXI requirements with engine power limitation percentages of 25%, 0% (hybrid option 1), and 15% (hybrid option 2), respectively. From an economic standpoint, the liquid hydrogen-based system has competitive costs compared to the dual-fuel diesel-electric system, with costs of 2.1 and 2.5 dollars per kilogram for hybrid system options 1 and 2, respectively.

Keywords: EEXI, EPL, alternative fuels, LNG carrier, economic analysis

INTRODUCTION

The transport of goods worldwide generates multiple exhaust gas emissions that have negative effects on the environment. These emissions include carbon monoxide (CO), carbon dioxide (CO_2), sulfur oxides (SO_x), particulate matter, and nitrogen oxides (NO_x) [1–3]. Stricter rules on greenhouse gas emissions (GHG) in the maritime industry have become a recent topic of debate due to the fact that over 90% of global trade is transported by ships [4, 5]. Shipping is responsible for more than 5% of overall SO_x emissions and 3% of overall CO_2 emissions [1]. To address this issue, the International Maritime Organization (IMO) has introduced several regulations aimed at promoting energy efficiency and reducing emissions from ships [6]. One such regulation is the Energy Efficiency Existing Ship Index (EEXI), which aims to improve the energy efficiency of existing ships and ensure that they meet minimum requirements for carbon emissions. The EEXI is part of the IMO's strategy to reduce greenhouse gas emissions from international shipping by at least 50% by 2050 [7, 8]. It is based on a calculation of a ship's Energy Efficiency Design Index (EEDI), which assesses a ship's carbon emissions based on its size, speed, and other design features [9, 10]. The EEXI uses a similar methodology and calculation to determine the energy efficiency rating of existing ships. Ships that fail to meet the minimum energy efficiency requirements set by the EEXI must take measures to reduce their emissions or face penalties. The EEXI regulation is a significant step towards reducing emissions from the shipping industry and improving energy efficiency. However, it presents challenges for ship owners and operators who must comply with the new standards while ensuring the economic viability of their vessels [11].

Various applications can be implemented on marine vessels to comply with EEXI requirements, including hull cleaning, design modifications, energy-saving devices, route optimisation, engine modifications, engine power limitation (EPL), and shaft power limitation (ShaPoLi) [12, 13]. Alternative energy or waste heat recovery systems can also be implemented to reduce the accommodation service resourced load [13, 14]. Cleaning the hull and propeller surfaces can reduce water resistance and save up to 5% in fuel, while improvements to the propeller design, such as variable structure propellers, can increase energy efficiency by up to 5% when compared to conventional propellers [15–17].

Engine power limitation is a highly applicable and easy method for older vessels to comply with EEXI requirements because minimal modifications are necessary. EPL ensures a changeable limit on the maximum continuous rating (MCR) power output, which also limits the vessel's speed. It can be implemented using a mechanical stopping screw for mechanical engines or fuel-limiting software for electronic engines. Moreover, several studies have investigated the potential of alternative propulsion systems and fuels to improve energy efficiency and reduce emissions in the shipping industry, including the use of LNG and LH_2 fuels in hybrid propulsion systems [18, 19] and the potential for engine power limitation (EPL) systems to improve the energy efficiency of diesel-electric dual-fuel propulsion systems [12]. These studies highlight the importance of considering a range of factors, including technical feasibility, safety considerations, and economic viability, when evaluating alternative propulsion systems and fuels for compliance with EEXI standards.

Moreover, there are many projects aimed at using fuel cell engines onboard ships to reduce emissions. The ZEMSHIP program aimed to operate a hybrid vessel employing proton exchange membrane fuel cells (PEMFCs), batteries, and compressed hydrogen from 2008 to 2010 [20]. The supply vessel, Viking Lady, adopted a hybrid propulsion system of dual-fuel diesel-electric engines (DFDE) and a molten carbonate fuel cell (MCFC) to provide secondary power as a part of the low-pollution vessel project (Fellow Vessel). The Viking Lady was the first hybrid ship to use an MCFC [21]. Hybrid engines with high-temperature fuel cells can be used in large ships by reforming hydrocarbon fuels [22]. However, due to their CO_2 emissions, reforming fossil fuels is unable to achieve the higher energy efficiency criterion. Korkmaz et al. conducted a comparative environmental study that examined the CO_2 reduction potentials of a ship using phosphoric acid fuel cells (PAFC), MCFC, and a diesel engine, and found that a 50% CO_2 emission reduction is hard to achieve [23]. In order to use hydrogen fuel onboard ships, it should be stored in compressed or liquefied forms. Compressed hydrogen storage techniques can be used at high pressures up to 800 bar, which results in a storage density of less than 39 kg/m^3 [24]. Alternatively, liquefied hydrogen (LH_2) can be stored at atmospheric pressure and a temperature of -250 °C, which results in a higher density of 71 kg/m^3 [25]. Due to the substantial volume of fuel storage tanks on ships, it is impractical to bunker while at sea. Therefore, the high density of LH_2 makes it a good option for maritime vessels, especially for large ships. On the other hand, PEMFCs have many desirable properties that make them a good option for ships' propulsion systems. PEMFCs work at low temperature and pressure, which allows for quick startup [26]. They also have high power density and efficiency compared to other fuel cell types [27]. Additionally, PEMFCs exhibit superior heat and reaction stability compared to SOFCs and perform better at low engine loads compared to DFDE engines [28].

The research gap in the previous literature on studying EEXI, EPL systems, alternative fuels, and hybrid propulsion systems for ships lies in the need to evaluate their combined effectiveness. While EPL and hybrid propulsion systems are individual solutions for improving energy efficiency and reducing emissions, their combined effectiveness has not been thoroughly studied. This study aims to contribute to this growing body of research by evaluating the potential of hybrid propulsion systems that combine LH_2 and LNG fuels, as well as the use of the EPL system for improving energy efficiency in DFDE ship propulsion systems. Additionally, this research focuses on several factors, including compliance with EEXI standards, fine-tuning fuel ratios, installation requirements, and economic feasibility. The investigated case study focuses on an LNG carrier and provides valuable insights for ship owners and operators who are seeking to comply with regulations and improve the environmental and economic performance of their vessels.

SYSTEM DESCRIPTION

LNG CARRIER VESSEL SPECIFICATIONS

The present case study is one of the Q-Max LNG carriers operated by Qatargas II, with an IMO number of 9337755. The vessel is currently berthed at the Ras Laffan terminal in Qatar. Its gross tonnage is 163,922, and its deadweight is 130,102. Gross tonnage refers to the total enclosed volume of a ship, while deadweight refers to the maximum weight of cargo, fuel, and supplies that a ship can carry. The vessel's main dimensions are 345 m for overall length, 53 m for breadth, and 12 m for summer draft. Table 1 summarises the main specifications for the ship [29, 30], including information such as its propulsion system, cargo capacity, and crew size. The vessel is powered by 2 MAN B&W 7S70ME-C two-stroke low-speed diesel engines, which have a total output power of 43.54 MW at 91 rpm.

Tab 1. Details of the selected vessel

Item	Value
Vessel classification	LNG tanker
Port of registry	Marshall Islands
Dimensions	345 (length) × 53 (beam) × 12 (draft) in m
Deadweight	130,102 ton
Cargo volume	266,000 m^3
Speed	19 knots
Engine	Dual-fuel diesel-electric engine
Installed power	43,540 kW (58,390 hp) at 91 rpm
Propulsion	2 x MAN B&W 7S70ME-C diesel engines
Main engine SFC	175 g/kWh
Liquefied natural gas fuel consumption	4.75 tons per hr

LNG CARRIER PROPULSION SYSTEM OPERATED BY DUAL-FUEL DIESEL-ELECTRIC ENGINE

Fig. 1 depicts a typical propulsion system operated by a DFDE for LNG ships. The LNG is stored at a pressure less than 1.2 bar and a temperature of -163 °C. During ship operations, the LNG's boil-off gas (BOG) is utilised as fuel to operate the main engines [31]. The compressor pressurises the BOG before supplying it to the DFDE system. The produced BOG is not enough to run the DFDE during operations. Therefore, the LNG fuel pump, submerged in the fuel tank, is used to transfer liquefied natural gas to the fuel vaporiser. The pump raises the LNG's pressure to 6 bar, at which point it is vaporised into natural gas. In a BOG vaporiser, the liquefied natural gas is heated using glycol water. After being heated to the required inlet temperature, which usually ranges from 25 °C to 35 °C, the LNG and boil-off gas are fed to the DFDE.

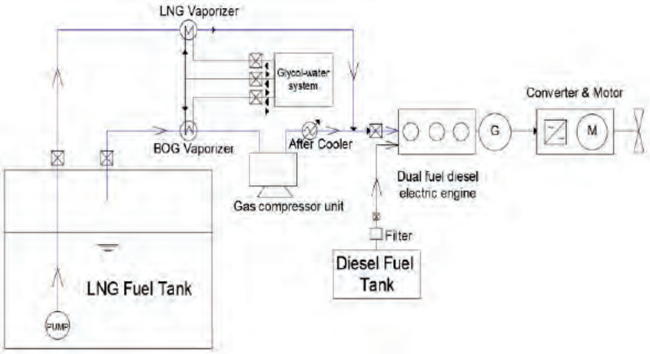


Fig. 1. LNG carrier propulsion system operated by dual-fuel diesel-electric engine

LNG CARRIER PROPULSION SYSTEM OPERATED BY HYBRID ENGINES

Fig. 2 shows the hybrid propulsion system of an LNG carrier, which operates using LNG and LH_2 fuels. The method for using the produced BOG in the liquefied gas storage tanks in the hybrid system is similar to that of the DFDE system explained earlier. PEMFC requires hydrogen at a pressure greater than 3 bar, which is achieved by pressurising the LH_2 using a submerged pump in the fuel tank. The BOG–LH_2 mixture is then pressurised using a compressor to the required inlet pressure for the fuel cell. Meanwhile, glycol water heats the pressurised liquid hydrogen and supplies it to the PEMFC electrode. The air is compressed and cooled before being delivered to the cathode of the PEMFC stack. Any unreacted hydrogen gas that passes through the fuel cell anode is recirculated back to the inlet line. At the cathode, the produced water vapour is discharged to the atmosphere.

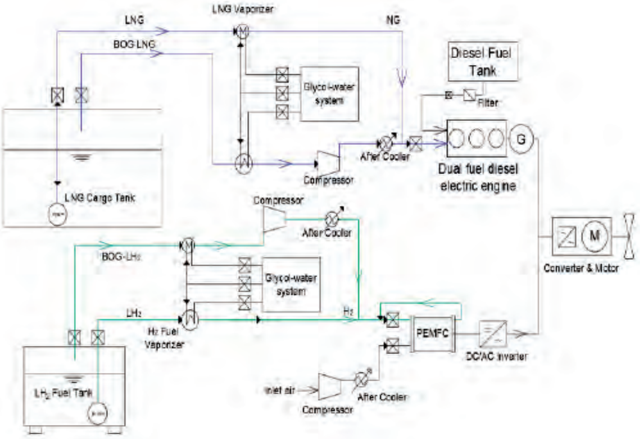


Fig. 2. LNG carrier hybrid propulsion system operated by LNG and LH_2 fuels

ASSUMPTIONS FOR THE CURRENT CASE STUDY

The assumed ship route for the case study involves transporting LNG between Ras Laffan port in Qatar and Vizag port in India, as shown in Fig. 3. Ras Laffan port is one of the largest LNG export facilities in the world, with the largest artificial harbour and a strategic location on the international maritime trade route [32]. India is currently the world's fourth-largest importer of LNG, with Qatar contributing 42% of India's imports and making it the top supplier of liquefied natural gas to India [33]. Table 2 provides a description of the voyage scenario and the schedule for the assumed 18 round trips per year of the vessel, including information such as the cargo capacity, loading and unloading times, and estimated fuel consumption for each leg of the journey.

Fig. 3. LNG carrier case study vessel and ship route

Tab. 2 Voyage circumstances for the case study vessel

Voyage	**Operating conditions**	**Voyage time**	**Engine working time**	**BOG producing time**
Loaded	LNG loading, h.	32	-	-
	Sea routing, h.	197	197	197
Ballast	LNG discharging, h.	32	-	-
	Sea routing, h.	197	197	197
Overall	Two-way trip in hours	455	395	395
	Two-way trip in days	19	17	17
Number of annual round trips	18	-	-	-

The specifications of the selected PEMFC module, which is used in the hybrid propulsion system, are listed in Table 3. The Ballard 200 kW PEMFC system is designed to provide zero-emission power to ships. The selected PEMFC module is specifically developed and tested for marine environments, and it has been approved by Det Norske Veritas (DNV) ship class for marine applications. The module is scalable from 200 kW to MWs to accommodate the power requirements of different ships based on the demands of their routes [34]. To comply with safety requirements, onboard the case study vessel, liquid hydrogen tanks are stored in IMO class C tanks, with vacuum-perlite insulation and stainless steel 304 tanks being used [35]. For this study, the capacity of the LH_2 tank was estimated by adding a 15% margin to the calculated amount of liquid hydrogen. This margin was added to ensure that the calculated storage volume would cover the required power onboard the ship. Additionally, it is difficult to maintain the vacuum insulation of liquid gas storage tanks, particularly for large volumes, which further justifies the use of the margin.

Tab. 3 PEM fuel cell main specifications [34, 36]

Rated power	**200 kW**
Minimum power	55 kW
Voltage	350–720 VDC
Volume	0.5 m^3 without H_2 storage
Dimensions (mm)	1209 × 741 × 2195
Efficiency	53.5% @ nominal power
Peak efficiency	60% @ 50% power
Ambient temperature	-30 °C to +40 °C
Emission	Water vapour
Operating temperature	60–65 °C
Lifetime	40,000 – 80,000 hours
Certifications	DNV-type approval

From an economic viewpoint, the following capital costs have been assumed for the current study. The cost of the dual-fuel engine is assumed to be 520 $/kW [37]. The cost of the PEMFC stack is assumed to be 150 $/kW, while the cost of the PEMFC system is assumed to be 210 $/kW [38, 39]. The cost of the liquefied natural gas vaporiser is assumed to be 40 $/kW, while the cost of the liquid hydrogen vaporiser is assumed to be 60 $/kW. The cost of the natural gas compressor is assumed to be 1200 $/kW [40], while the cost of the air compressor is assumed to be 450 $/kW [41]. Finally, the cost of the after-cooler is assumed to be 90 $/kW [42–44]. In addition, maintenance and repair costs are assumed to be 6% of the capital costs, while operating supplies costs are assumed to be 15% of the maintenance and repair costs [45]. According to the latest fuel prices, the prices of natural gas and hydrogen fuels are 190 $/ton and 5200 $/ton, respectively [46, 47].

METHODOLOGY AND MODELLING

In this section, the energy efficiency existing index and economic modelling of conventional DFDE and hybrid propulsion systems operated by alternative fuels are assessed. The fuel ratios of LNG and LH_2 that satisfy EEXI-IMO requirements for both the hybrid and DFDE propulsion systems are estimated. Finally, the breakeven price of LH_2 for the hybrid systems is estimated in the economic analysis.

ATTAINED AND REFERENCE ENERGY EFFICIENCY EXISTING INDEX VALUES

The Energy Efficiency Existing Ship Index is a regulatory requirement under the International Maritime Organization's (IMO) MARPOL Annex VI regulations. The EEXI requirements were adopted by the IMO's Marine Environment Protection Committee (MEPC) in November 2020 and became mandatory on January 1, 2023. Starting on that date, all ships over 400 gross tonnage (GT) will be required to have an EEXI that meets the required level of energy efficiency, based on the ship's technical specifications, design characteristics, and operational profile. Each existing ship must meet two EEXI parameters specified by the IMO in 2022: the required and the attained. In order to meet the minimum energy efficiency standards recommended by the IMO, the attained EEXI (expressed in gCO_2/ton.nm) must be equal to or less than the required EEXI. The required EEXI for each ship is based on its baseline value of the Energy Efficiency Design Index (EEDI) after accounting for a reduction factor as shown in Eqs. (1) and (2) [48, 49].

$$\text{EEXI baseline value} \; = 2253.7 \times \text{DWT}^{-0.474} \tag{1}$$

$$\text{Required EEXI} \; = \left(1 - \frac{\text{X}}{100}\right) \times \text{EEXI baseline value} \tag{2}$$

where (DWT) is the ship's deadweight in tons and (X) is the reduction factor, based on the ship type, and is 30% for LNG carriers.

The attained EEXI value for LNG carriers, on the other hand, depends on several factors such as the type of fuel used in the main and auxiliary engines, the ship's deadweight (DWT) in tons, and other ship specifications, as well as the sea state. The formula for calculating the attained EEXI for diesel-electric LNG carriers (expressed in gCO_2/ton.nm) is presented in Eq. (3) [48–50]. In this case, dual-fuel diesel-electric engines do not have separate main engines (MEs) and auxiliary engines (AEs) but have a number of 4-stroke dual-fuel gensets, all acting as MEs.

$$\text{EEXI}_{\text{attained}} = \frac{(\text{P}_{\text{ME}} + \text{P}_{\text{AE}}) \times \begin{bmatrix} (C_{f\text{ME(pilot)}} \times \text{SFC}_{\text{ME(pilot)}}) + \\ (C_{f\text{ME(gas)}} \times \text{SFC}_{\text{ME(gas)}}) \end{bmatrix}}{f_i \cdot f_c \cdot f_w \cdot \text{Capacity} \cdot \text{V}_{\text{ref}}} \tag{3}$$

where (P_{ME}) and (P_{AE}) are the main and auxiliary engines powers, respectively, (SFC_{ME}) is the specific fuel consumption at 75% for the main engines, respectively, (C_f) is the fuel conversion factor to CO_2 emissions, and (V_{ref}) is the vessel speed in knots at the summer load line. (f_i) is the capacity factor for any technical/regulatory limitation on ship capacity, (f_c) is the cubic capacity correction factor for chemical tankers, gas carriers and RO-RO passenger ships, and (f_w) is the coefficient for the decrease in ship speed due to weather and environmental conditions. Capacity is the deadweight tonnage (DWT) for LNG carriers.

(P_{ME}) is the engine power, assumed to be 75% of the rated power in normal conditions. In the case of using electric propulsion and Engine Power Limitation (EPL), (P_{ME}) can be calculated using Eq. (4) [50].

$$\text{P}_{\text{ME}} \; = \frac{\sum_{\text{i}=1}^{\text{n}} (0.83.\, \text{MPP}_{limit})}{\eta_{(elec)}} \tag{4}$$

where (MPP_{limit}) is the rated limited output power in kW of electric engine (i), and ($\eta_{(elec)}$) is the electric systems' efficiencies including the transformer, converter, and propulsion motor.

In addition, (P_{AE}) used in Eq. (3) can be predetermined based on the main engine power as expressed in Eq. (5).

$$\text{P}_{\text{AE(MCR(ME)>10,000 kW)}} = \left[0.025.\left(\sum_{\text{i}=1}^{\text{nME}} \text{MCR}_{\text{ME}}\right)\right] + 250 \tag{5}$$

where (MCR) represents the maximum continuous rating power in kilowatts for the main engine (i), and (n) represents the number of main engines on the ship.

Calculating the reference ship speed (V_{ref}) depends on whether or not it complies with Energy Efficiency Design Index (EEDI) requirements. If the ship complies with EEDI requirements, (V_{ref}) can be obtained from the certified speed-power curve. If the ship does not comply with EEDI requirements, an approximated speed-power curve can be used to determine (V_{ref}). If the ship's sea trial results are validated by tank tests but it does not comply with EEDI requirements, (V_{ref}) can be calculated using Eq. (6) [48].

$$\text{V}_{\text{ref}} \; = \text{V}_{\text{s}} \times \left(\frac{\text{P}_{\text{ME}}}{\text{P}_{\text{s}}}\right)^{\frac{1}{3}} \tag{6}$$

where (V_s) is the sea trial speed, and (P_S) is the main engine power according to (V_s). For tankers, container ships, or bulk carriers not subject to the EEDI but whose sea trials have been calibrated by the tank test under the design load draught and sea conditions, (V_{ref}) can be calculated using Eq. (7).

$$\text{V}_{\text{ref}} \; = \text{k}^{\frac{1}{3}} \times \left(\frac{\text{DWT}_{\text{s}}}{\text{Capacity}}\right)^{\frac{2}{9}} \times \text{V}_{\text{s}} \times \left(\frac{\text{P}_{\text{ME}}}{\text{P}_{\text{s}}}\right)^{\frac{1}{3}} \tag{7}$$

where (DWT_s) is the deadweight regarding the design load draught. The scale coefficient is represented by k depending on the ship type and capacity [48].

In the case of using liquefied fuels for operating ship engines, the boil-off gas rate (BOR) can be calculated using Eq. (8). It shows the amount of evaporated LNG fuel per day as a share of the overall cargo (%/day) [51–53].

$$\mathrm{BOR} = \left(\frac{\mathrm{Q}}{\mathrm{H_{latent}}} \times 3600 \times 24\right) \times \frac{100}{\rho_{\mathrm{LH_2}} \mathrm{V_{c\,arg\,o}}} \tag{8}$$

where (Q) is the power of the heat exchange rate in the storage tanks (kW), (ρ) is the LNG density in kg/m^3, and (H_{latent}) is the vaporisation heat in kJ/kg. The average BOR values for new LNG tankers range from 0.1 to 0.15% /day for the laden voyage and from 0.06 to 0.1 %/day for the ballast voyage [54].

ECONOMICS MODELLING

A system's initial investment cost, or CAPEX, is made up of both direct and indirect costs [55]. Direct costs include the installation and purchase costs of the equipment, while indirect costs include incidental costs such as system design, manpower, and surcharges. The formula for calculating CAPEX is shown in Eq. (9), which takes into account both direct and indirect costs associated with the installation of the equipment.

$$\mathrm{CAPEX} = \sum_{1}^{x} \mathrm{TP_{C,x}}\,(1 + \mathrm{IPER_{c,x}}) \tag{9}$$

where (TP_c) represents the total purchase and initial costs of the equipment (x), and ($IPER_c$) represents the percentage of indirect costs related to (TP_c) costs. ($IPER_c$) can be calculated using the following Eq. (10) [56, 57]:

$$\mathrm{IPER_c} = \frac{\mathrm{C_{lab}} + \mathrm{C_{mat}} + \mathrm{C_{overhead}} + \mathrm{C_{reg}} + \mathrm{C_{test}}}{\mathrm{TP_c}} \tag{10}$$

where (C_{lab}) represents the indirect labour costs for equipment installation, like wages, benefits, and training costs for the workers who install the equipment. (C_{mat}) is the indirect material costs, such as costs of materials that are necessary for the installation of the equipment but are not part of the equipment itself. Examples include wiring, cables, nuts, bolts, and other small parts. ($C_{overhead}$) represents the overhead indirect costs, like costs associated with running the business that cannot be directly attributed to the installation of the equipment. (C_{reg}) represents the indirect permitting and regulatory costs, like costs associated with obtaining the necessary permits and complying with regulatory requirements for the installation of the equipment. (C_{test}) is the testing and commissioning indirect costs, for example, costs associated with testing and commissioning the equipment to ensure that it operates correctly.

On the other hand, the overall operating expenses (OPEX) of a propulsion system over the course of its lifetime include the costs of fuel, electricity, and operations and maintenance (O&M). The value of operating expenditures is divided into four main components as shown in Eq. (11).

$$\mathrm{OPEX} = \mathrm{C_{O\&M}} + \mathrm{C_{fuel}} + \mathrm{C_{elec.}} + \mathrm{C_{fixed}} \tag{11}$$

where ($C_{O\$M}$) is the operating and maintenance costs, (C_{fuel}) is the total fuel costs, ($C_{elec.}$) is the electricity consumption for operating the system, and (C_{fixed}) is the fixed charges like insurance. (C_{fixed}) can be assumed as 0.7% of the fixed capital investment [45].

Net present value (NPV) is the difference between the present value of cash inflows and the present value of cash outflows over a period of time. The investment will be more valuable if NPV is higher than 0. The NPV formula is given in Eq. (12) [58, 59].

$$\mathrm{NPV} = \sum_{t=1}^{N} \frac{\mathrm{C_{tot}}}{(1+\mathrm{i})^{\mathrm{t}}} - \mathrm{C}_o \tag{12}$$

where (t) is the finances interval, (N) denotes the lifetime, (C_{tot}) denotes the net finances at interval (t), (C_o) denotes the current amount of capital expenditure, and (i) refers to the annual interest rate. (i) ranges from (2% to 8%) and from (8% to 30%) for industrialised and developing countries, respectively [60]. (i) is assumed to be 5% for the current study.

RESULTS AND DISCUSSION

ENERGY EFFICIENCY RESULTS

Fig. 4 shows the energy efficiency index values for existing LNG carriers based on ship deadweight. The calculated energy efficiency index value for the case study, which is operated by LNG fuel without installing an EPL system, is 7.19 gCO$_2$ per ton-nautical mile. This value does not meet the IMO-EEXI standard. To comply with the reference EEXI value, an EPL system should be installed for the DFDE propulsion system.

Reducing the consumption of LNG and increasing the power produced by hydrogen fuel cells are two important factors that can reduce the attained EEXI for a hybrid propulsion system. In order to comply with the IMO-EEXI standard for the year 2023, a hybrid system is incorporated with variable fuel cell and hydrogen output powers. The fuel cells should generate 11.6 MW of the required propulsion power, or 26.64% of the total maximum continuous rating (MCR), to comply with the reference EEXI value. For this scenario, hybrid system option 1 will attain an energy efficiency index value of 5.93 gCO$_2$ per ton-nautical mile, which complies with the IMO-EEXI value. Hybrid system option 1will not require the installation of an EPL system. On the other hand, a proposed hybrid propulsion system, operated by 5.8 MW PEMFC with an installed EPL system, will be investigated in the current study. This system, hybrid system option 2, is being investigated to show the effect of using EPL in the hybrid system while reducing the fuel cell output power.

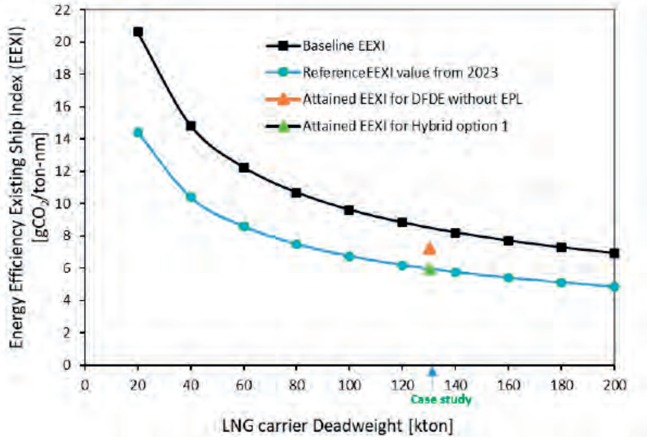
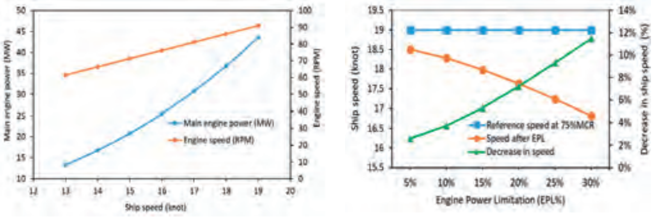


Fig. 4. Reference EEXI for the LNG carriers at different capacities

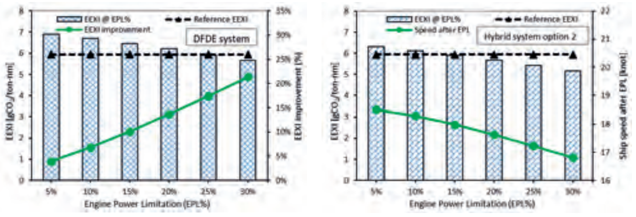
Limiting engine power is a method that can be used to reduce a ship's EEXI. This involves reducing the maximum power output of the ship's engines, which in turn limits the ship's speed. By reducing the ship's speed, the fuel consumption is lowered, resulting in lower emissions. To implement engine power limitation, the ship's engine performance needs to be analysed to determine its maximum power output. The ship's operational profile also needs to be analysed to determine the most effective engine power limitation strategy. Once the optimal strategy is determined, it needs to be implemented through the use of engine control systems that can limit the engine's maximum power output based on the ship's operational requirements. From the case study sea trial report, the relationship between ship speed, engine output power, and RPM can be drawn, as shown in Fig. 5 (a). Based on the case study specifications and main engine performance, the effect of engine power limitation on the ship speed is shown in Fig. 5 (b). The reference ship speed of 19 knots is reduced by 4%, 7%, and 11% when the engine power is limited by 10%, 20%, and 30%, respectively.



(a) *(b)*

Fig. 5. Relation between ship speed and main engine power (I) as well as EPL (II)

Fig. 6 shows the values of the attained EEXI at different EPL values for the DFDE and hybrid system option 2. It can be noted that the DFDE system has relatively high EEXI values compared to the hybrid system. As a result, it will require high power limitation values to comply with the reference EEXI compared to the hybrid system. The reference value for the EEXI for the current case study is 5.941 gCO_2/ton-nautical mile. In order to comply with the reference EEXI, the main engine power should be limited by 25% and 15% for the DFDE and hybrid option 2 systems, respectively. In these scenarios, the attained EEXI will improve by 17% and 10%, respectively. Moreover, the operational ship speed will be reduced from 19 knots to 17.2 knots and 17.98 knots with speed reduction percentages of 9% and 5%, respectively.



(a) *(b)*

Fig. 6. EEXI at different EPL for DFDE system (i) and hybrid system option 2 (ii)

Fig. 7 illustrates the calculated weight percentages of liquid hydrogen and natural gas fuels in the DFDE and hybrid systems to comply with the required IMO-EEXI value. To achieve the requirements, only hybrid system option 1 can be used to power the case study vessel without installing an EPL system. The required weight percentages of liquid hydrogen fuel are 4% and 7% of the overall LNG and LH_2 fuels weight to comply with the IMO-EEXI requirements for hybrid system options 1 and 2, respectively. In comparison to a traditional liquefied natural gas system, the energy percentage is between 26.64% and 13.32% of the maximum continuous rating, respectively. In addition, proton exchange membrane fuel cells (PEMFCs) that use hydrogen have higher power-generating efficiency than conventional natural gas-operated systems.

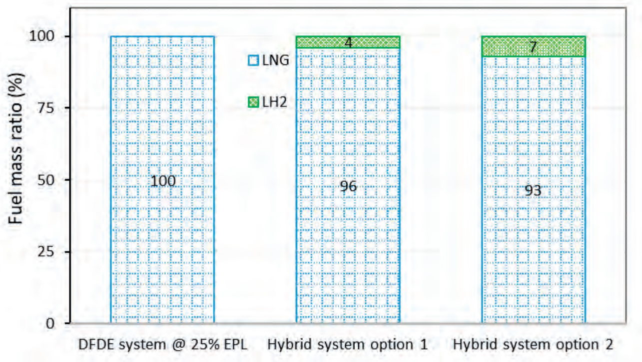


Fig. 7. Fuel mass percentage for conventional system and the hybrid systems

COMPARING THE VOLUME RATIO OF THE PROPULSION ENGINES

The required fitting space of the propulsion engines, which includes the DFDE engine, fuel cell, and liquid hydrogen tank volumes, can be seen in Fig. 8. Hybrid system options 1 and 2 require higher volumes than the conventional DFDE system by 93.76% and 48.84%, respectively. A significant contributor to the increased capacity of the overall system is the volumetric increase of the liquid hydrogen storage tanks, which accounts for 52.84% and 34.16% of the overall volume rise in hybrid system options 1 and 2, respectively. The volume of the PEMFCs is less than that of the DFDE engines, accounting for 14.91% and 9.73%, respectively, of the entire system capacities. However, the fitting of extra tubes or valves cannot have a considerable influence on the propulsion area because they are mounted on the ship deck. Table 4 displays the required capacities for fuel cell and liquid hydrogen tanks for the two hybrid systems.

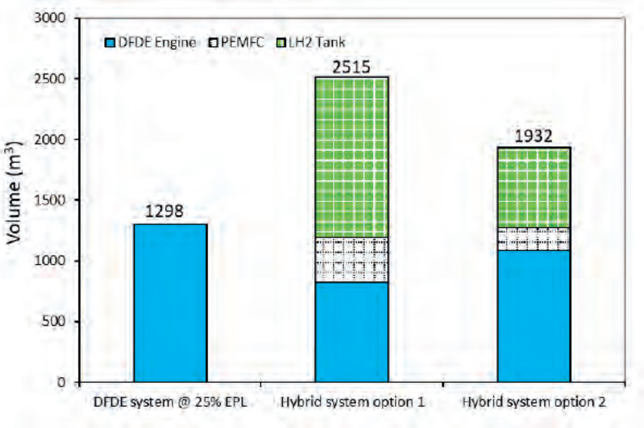


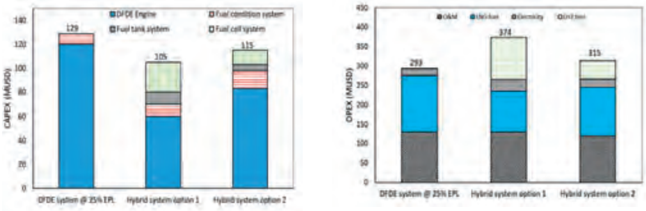
Fig. 8. Comparing the required engine volumes for the investigated propulsion systems

Tab. 4 Fuel cell and storage tank volumes onboard the ship

Hybrid system	Option 1	Option 2
Tank type	IMO type C	IMO type C
Tank volume	1320 m^3	660 m^3
PEMFC's power	11,600 kW	5,800 kW
Number of stacks	58	4
PEMFC volume	340 m^3	160 m^3

ECONOMIC RESULTS

Fig. 9 (a) shows the capital expenditures for the conventional DFDE and hybrid propulsion systems. The CAPEX of hybrid system option 1 and option 2 are 18.6% and 10.8% less than that of the conventional liquefied natural gas system, respectively. This is due to the low hydrogen consumption rate for the hybrid systems, which does not have a high impact on the CAPEX costs. Additionally, compared to using a DFDE system, the CAPEX cost of producing a lower power output by utilising a fuel cell is quite low. Therefore, future fuel cell technology advances and an increase in the volume of stack manufacturing might accelerate the adoption of hybrid propulsion systems. On the other hand, using hybrid systems will increase the operating expenditures for propulsion systems, as shown in Fig. 9 (b). This is due to the fuel cost of liquid hydrogen being more than liquefied natural gas and due to the additional equipment required for producing electricity in the hybrid system. Additionally, the PEM fuel cell stack will need to be replaced every 43,800 working hours (5 years) during the ship's expected lifetime of 25 years. The cost of fuel cell stacks, included in the operating and maintenance costs (O&M), will be 8.7 and 4.35 million USD for hybrid system options 1 and 2, respectively, over the ship's lifetime. The liquid hydrogen cost to operating expenditure ratio is highest for hybrid system options 1 and 2, at 29.4% and 15.8%, respectively. Compared to the liquefied natural gas system, the cost of liquefied natural gas fuel is reduced by 27.5% and 13.7% for hybrid system options 1 and 2, respectively. Finally, the total operating costs for hybrid system options 1 and 2 are estimated to be 374 and 315 million USD, respectively. These costs represent an increase of 27.6% and 7.5%, respectively, compared to the DFDE system.



(a) (b)

Fig. 9. CAPEX and OPEX expenses for the investigated propulsion systems

The life cycle costs of each propulsion system are the sum of the CAPEX and OPEX expenses, as shown in Fig. 10. The life cycle cost of the hybrid system increases as the EEXI requirements become more challenging. In comparison to the liquefied natural gas system, the life cycle cost for hybrid system option 1 and option 2 increased by 13.5% and 1.9%, respectively. Based on the expected lower future prices for hydrogen fuels, the predicted life cycle costs for the hybrid systems can be reduced. Therefore, the cost of LH$_2$ fuel needs to be reduced to operate a hybrid propulsion system profitably and to comply with the new IMO emissions requirements. Consequently, this will increase the opportunities for using hydrogen fuel onboard ships.

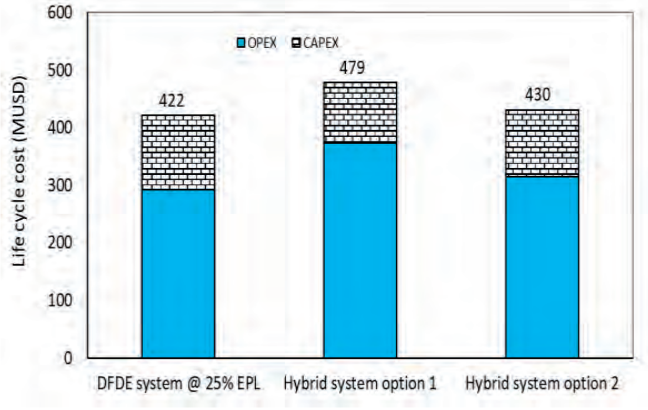
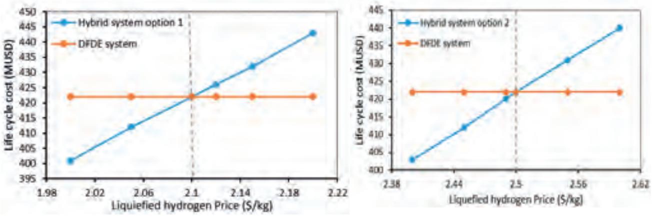


Fig. 10. Life cycle costs of the investigated propulsion systems

Fig. 11 (a and b) illustrates the breakeven liquid hydrogen fuel prices required to achieve the IMO-EEXI value for the hybrid systems compared to the conventional natural gas system. The results show that the cost of viable liquid hydrogen fuel is expected to be \$2.10 per kg for hybrid system option 1 and \$2.50 per kg for option 2. The left region between the life cycle cost of the conventional LNG and the hybrid systems, as shown in Fig. 11, illustrates the economic range for using the hybrid system. However, the right region in the figure is more costly compared to the conventional DFDE propulsion system.



(a) (b)

Fig. 11. Breakeven of liquid hydrogen fuel price for achieving IMO-EEXI requirements

Finally, the price of hydrogen fuel, as well as the CAPEX and OPEX expenses for the fuel cell engines, are key factors for a cost-effective hybrid propulsion system onboard a ship. Based on the current case study, the LNG-LH_2 hybrid system may be a cost-effective choice that satisfies EEXI requirements at a hydrogen fuel cost of less than \$2.10 per kg.

CONCLUSIONS

In conclusion, the current paper has explored the potential of using hybrid propulsion systems that combine LH_2 and LNG fuels, as well as the use of the engine power limitation (EPL) system for improving energy efficiency for dual-fuel diesel-electric engine (DFDE) ship propulsion systems. The study has focused on several factors, including compliance with the EEXI standards set by the IMO, fine-tuning fuel ratios, installation requirements, and economic feasibility. As a case study, an LNG carrier was investigated. The main findings from the current study are as follows:

- From the energy efficiency viewpoint, the DFDE and two hybrid systems could be adjusted to comply with IMO-EEXI requirements with EPL percentages of 25%, 0% (hybrid option 1), and 15% (hybrid option 2), respectively. The attained energy efficiency existing index value for the hybrid system option 1, is 5.93 gCO_2 per ton-nm. In order to comply with the reference EEXI, the main engine power should be limited by 25% and 15% for the DFDE and hybrid option 2 systems, respectively. In these scenarios, the attained EEXI will be improved by 17% and 10%, respectively. Moreover, the operational ship speed will be reduced from 19 knots to 17.2 knots and 17.98 knots with speed reduction percentages of 9% and 5%, respectively. Finally, options 1 and 2 of the hybrid system require higher volumes than the natural gas system by 93.76% and 48.84%, respectively.
- From an economic viewpoint, the CAPEX expenses of the hybrid options 1 and 2 are 18.6% and 10.8% less than that of the conventional liquefied natural gas system, respectively. On the other hand, the OPEX expenses rise by 27.6% and 7.5%, respectively. Therefore, the total life cycle cost for the hybrid system options 1 and 2 increased by 13.5% and 1.9%, respectively. The LH_2-based system had competitive costs compared to the DFDE system, with costs of 2.1 and 2.5 dollars per kg corresponding to hybrid system options 1 and 2, respectively. Finally, the cost of hydrogen fuel needs to be reduced to operate a hybrid propulsion system profitably and to comply with the new IMO emissions requirements. Consequently, this will increase the opportunities for using hydrogen fuel onboard ships.

Finally, the findings of the present study provide valuable insights for ship owners and operators looking to comply with regulations and improve the environmental and economic performance of their vessels. As the shipping industry continues to face increasing pressure to reduce emissions and improve energy efficiency, the use of innovative technologies such as hybrid propulsion systems and EPL technology will play an increasingly important role in achieving these goals.

REFERENCES

1. H. Huang *et al.*, "Inland ship emission inventory and its impact on air quality over the middle Yangtze River, China," *Sci. Total Environ.*, vol. 843, p. 156770, 2022, https://doi.org/10.1016/j.scitotenv.2022.156770.

2. B. Ryu, P. A. Duong, and H. Kang, "Comparative analysis of the thermodynamic performances of solid oxide fuel cell–gas turbine integrated systems for marine vessels using ammonia and hydrogen as fuels," *Int. J. Nav. Arch.*

Ocean Eng., p. 100524, 2023, https://doi.org/10.1016/j.ijnaoe.2023.100524.

3. N. R. Ammar and I. S. Seddiek, “Hybrid/dual fuel propulsion systems towards decarbonization: Case study container ship,” *Ocean Eng.*, vol. 281, p. 114962, 2023, https://doi.org/10.1016/j.oceaneng.2023.114962.
4. M. M. Elgohary, I. S. Seddiek, and A. M. Salem, “Overview of alternative fuels with emphasis on the potential of liquefied natural gas as future marine fuel,” *Proc. IMechE, Part M: Journal of Engineering for the Maritime Environment,* vol. 229, no. 4, pp. 365-375, 2014, doi: 10.1177/1475090214522778.
5. V. Yalama, O. Yakovleva, V. Trandafilov, and M. Khmelniuk, “Future sustainable maritime sector: Fishing carriers and their adoption to the environmental regulations. Part I,” *Pol. Marit. Res.*, vol. 29, no. 3, pp. 69-77, 2022, doi:10.2478/pomr-2022-0027.
6. O. Konur, M. Bayraktar, M. Pamik, B. Kuleyin, and M. Nuran, “The energy efficiency gap in Turkish maritime transportation,” *Pol. Marit. Res.*, vol. 26, no. 3, pp. 98-106, 2019, doi:10.2478/pomr-2019-0050.
7. IMO, “Resolution MEPC.254(67). Guidelines on survey and certification of the energy efficiency design index (EEDI). International Maritime Organization,” 2014.
8. IMO, “Energy efficiency of ships, comments received by the correspondence group on possible introduction of EEDI Phase 4, Submitted by Japan. Marine environment protection committee, 75th session agenda item 6,” 2019.
9. IMO, “Fourth IMO Greenhouse Gas Study 2020: Safe, secure and efficient shipping on clean oceans,” London: International Maritime Organization (IMO), 2020.
10. M. Kalajdžić, M. Vasilev, and N. Momčilović, “Evaluating an inland waterway cargo vessel’s energy efficiency indices,” *Pol. Marit. Res.*, vol. 29, no. 2, pp. 27-34, 2022, doi:10.2478/pomr-2022-0014.
11. V. Yalama, O. Yakovleva, V. Trandafilov, and M. Khmelniuk, “Future sustainable maritime sector: Energy efficiency improvement and environmental impact reduction for fishing carriers older than 20 years in the fleet Part II,” *Pol. Marit. Res.*, vol. 29, no. 3, pp. 78-88, 2022, doi:10.2478/pomr-2022-0028.
12. M. Bayraktar and O. Yuksel, “A scenario-based assessment of the energy efficiency existing ship index (EEXI) and carbon intensity indicator (CII) regulations,” *Ocean Eng.*, vol. 278, p. 114295, 2023, https://doi.org/10.1016/j.oceaneng.2023.114295.
13. E. Czermański *et al.*, “Implementation of the Energy Efficiency Existing Ship Index: An important but costly step towards ocean protection,” *Marine Policy,* vol. 145, p. 105259, 2022, https://doi.org/10.1016/j.marpol.2022.105259.
14. F. Baldi and A. Coraddu, “Appendix B - Towards halving shipping GHG emissions by 2050: the IMO introduces the CII and the EEXI,” in *Sustainable Energy Systems on Ships*, F. Baldi, A. Coraddu, and M. E. Mondejar, Eds. Elsevier, 2022, pp. 513-517.
15. A. Farkas, N. Degiuli, I. Martić, and C. G. Grlj, “Is slow steaming a viable option to meet the novel energy efficiency requirements for containerships?” *J. Clean. Prod.*, vol. 374, p. 133915, 2022, https://doi.org/10.1016/j.jclepro.2022.133915.
16. M. Schroer, G. Panagakos, and M. B. Barfod, “An evidence-based assessment of IMO’s short-term measures for decarbonizing container shipping,” *J. Clean. Prod.*, vol. 363, p. 132441, 2022, https://doi.org/10.1016/j.jclepro.2022.132441.
17. H. Wang, Y. Hou, Y. Xiong, and X. Liang, “Research on multi-interval coupling optimization of ship main dimensions for minimum EEDI,” *Ocean Eng.*, vol. 237, p. 109588, 2021, https://doi.org/10.1016/j.oceaneng.2021.109588.
18. S. E. Damian *et al.*, “Review on the challenges of hybrid propulsion system in marine transport system,” *Journal of Energy Storage,* vol. 56, p. 105983, 2022, https://doi.org/10.1016/j.est.2022.105983.
19. S. Hyeon, J. Lee, and J. Choi, “Evaluation of fuel gas supply system for marine dual-fuel propulsion engines using LNG and ammonia fuel,” *Energies*, vol. 15, no. 17, doi: 10.3390/en15176303.
20. Á. Benet, A. Villalba-Herreros, R. d’Amore-Domenech, and T. J. Leo, “Knowledge gaps in fuel cell-based maritime hybrid power plants and alternative fuels,” *J. Power Sources,* vol. 548, p. 232066, 2022, https://doi.org/10.1016/j.jpowsour.2022.232066.
21. J. Ahn, S. H. Park, S. Lee, Y. Noh, and D. Chang, “Molten carbonate fuel cell (MCFC)-based hybrid propulsion systems for a liquefied hydrogen tanker,” *Int. J. Hydrogen Energ.,* vol. 43, no. 15, pp. 7525-7537, 2018, https://doi.org/10.1016/j.ijhydene.2018.03.015.
22. L. van Biert and K. Visser, “Chapter 3 - Fuel cells systems for sustainable ships,” in *Sustainable Energy Systems on Ships*, F. Baldi, A. Coraddu, and M. E. Mondejar, Eds. Elsevier, 2022, pp. 81-121.
23. S. A. Korkmaz, K. E. Erginer, O. Yuksel, O. Konur, and C. O. Colpan, “Environmental and economic analyses of fuel cell and battery-based hybrid systems utilized as auxiliary

power units on a chemical tanker vessel," *Int. J. Hydrogen Energ.,* 2023, https://doi.org/10.1016/j.ijhydene.2023.01.320.

24. Z. Chen, Y. Chen, W. Wang, K. Lu, H. Yang, and W. Zhu, "Failure pressure analysis of hydrogen storage pipeline under low temperature and high pressure," *Int. J. Hydrogen Energ.,* vol. 45, no. 43, pp. 23142-23150, 2020, https://doi.org/10.1016/j.ijhydene.2020.06.129.

25. Y. Rong *et al.*, "Techno-economic analysis of hydrogen storage and transportation from hydrogen plant to terminal refueling station," *Int. J. Hydrogen Energ.,* 2023, https://doi.org/10.1016/j.ijhydene.2023.01.187.

26. A. Farsi and M. A. Rosen, "PEM fuel cell-assisted lithium ion battery electric vehicle integrated with an air-based thermal management system," *Int. J. Hydrogen Energ.,* vol. 47, no. 84, pp. 35810-35824, 2022, https://doi.org/10.1016/j.ijhydene.2022.08.153.

27. A. Pramuanjaroenkij and S. Kakaç, "The fuel cell electric vehicles: The highlight review," *Int. J. Hydrogen Energ.,* vol. 48, no. 25, pp. 9401-9425, 2023, https://doi.org/10.1016/j.ijhydene.2022.11.103.

28. A. S. Mohammed, S. M. Atnaw, A. O. Salau, and J. N. Eneh, "Review of optimal sizing and power management strategies for fuel cell/battery/super capacitor hybrid electric vehicles," *Energy Reports,* vol. 9, pp. 2213-2228, 2023, https://doi.org/10.1016/j.egyr.2023.01.042.

29. Marine Traffic, "MOZAH, LNG TankerLNG Tanker IMO: 9337755," https://www.marinetraffic.com/en/ais/details/ships/shipid:712524/mmsi:538003212/imo:9337755/vessel:MOZAH (accessed 25 March 2023.

30. Vessel tracking, "MOZAH (IMO 9337755) - LNG Tanker," https://www.vesseltracking.net/ship/mozah-9337755 (accessed 25 March 2023.

31. M. S. Khan *et al.*, "Graphical approach for estimating and minimizing boil-off gas and compression energy consumption in LNG regasification terminals," *J. Nat. Gas Sci. Eng.,* vol. 101, p. 104539, 2022, https://doi.org/10.1016/j.jngse.2022.104539.

32. Qatar Energy, "Ports Information," https://www.qatarenergy.qa/en/MarketingAndTrading/Pages/PortsInformation.aspx (accessed 3 March 2023.

33. Statista, "Distribution of liquefied natural gas imported into India in 2021, by country of origin," https://www.statista.com/statistics/1237488/lng-import-share-india-by-country/#:~:text=India's%20primary%20supplier%20of%20liquefied,world's%20fourth%2Dlargest%20LNG%20importer (accessed 2 March 2023.

34. Ballard, "Fuel cell power module for marine applications," https://www.ballard.com/docs/default-source/spec-sheets/fcwavetm-specification-sheet.pdf?sfvrsn=6e44dd80_12 (accessed 2 February 2023.

35. M. Cavo, E. Gadducci, D. Rattazzi, M. Rivarolo, and L. Magistri, "Dynamic analysis of PEM fuel cells and metal hydrides on a zero-emission ship: A model-based approach," *Int. J. Hydrogen Energ.,* vol. 46, no. 64, pp. 32630-32644, 2021, https://doi.org/10.1016/j.ijhydene.2021.07.104.

36. S. Dirkes, J. Leidig, P. Fisch, and S. Pischinger, "Prescriptive lifetime management for PEM fuel cell systems in transportation applications, Part I: State of the art and conceptual design," *Energ. Convers. Manage.,* vol. 277, p. 116598, 2023, https://doi.org/10.1016/j.enconman.2022.116598.

37. Y. Wang and L. A. Wright, "A comparative review of alternative fuels for the maritime sector: Economic, technology, and policy challenges for clean energy implementation," *World,* vol. 2, no. 4, pp. 456-481, 2021, doi: 10.3390/world2040029.

38. R. Jing *et al.*, "Economic and environmental multi-optimal design and dispatch of solid oxide fuel cell based CCHP system," *Energ. Convers. Manage.,* vol. 154, pp. 365-379, 2017, https://doi.org/10.1016/j.enconman.2017.11.035.

39. H. Xing, C. Stuart, S. Spence, and H. Chen, "Fuel cell power systems for maritime applications: Progress and perspectives," *Sustainability,* vol. 13, no. 3, 2021, doi: 10.3390/su13031213.

40. X. Tian, W. Jiao, L. Ren, S. Liu, and T. Liu, "Research on climate zoning indicators for operating environment of liquefied natural gas ambient air vaporizer," *Sustainable Cities and Society,* vol. 60, p. 102186, 2020, https://doi.org/10.1016/j.scs.2020.102186.

41. M. Sermsuk, Y. Sukjai, M. Wiboonrat, and K. Kiatkittipong, "Feasibility study of a combined system of electricity generation and cooling from liquefied natural gas to reduce the electricity cost of data centres," *Energy,* vol. 254, p. 124397, 2022, https://doi.org/10.1016/j.energy.2022.124397.

42. Y. Li and H. Luo, "Integration of light hydrocarbons cryogenic separation process in refinery based on LNG cold energy utilization," *Chemical Engineering Research and Design,* vol. 93, pp. 632-639, 2015, https://doi.org/10.1016/j.cherd.2014.04.009.

43. N. T. Stetson and R. C. Bowman, " Fuel cell system cost. Department of Energy Hydrogen and Fuel Cells Program Record," 2016.

44. R. E. Ciez and J. F. Whitacre, “Comparison between cylindrical and prismatic lithium-ion cell costs using a process based cost model,” *J. Power Sources,* vol. 340, pp. 273-281, 2017, https://doi.org/10.1016/j.jpowsour.2016.11.054.

45. M. S. Peters, K. D. Timmerhaus, and R. E. West, *Plant design and economics for chemical engineers*. McGraw-Hill, 2003.

46. MAN, “Hydrogen in shipping, MAN Energy Solutions,” https://www.man-es.com/campaigns/download-Q2-2023/Download/hydrogen-in-shipping/faffa612-4edc-4a2a-a5f9-df89c632a431/Future-Fuels-Hydrogen (accessed 30 March 2023).

47. EIA, *US Energy Information Administration, Natural Gas Statistics*, https://www.eia.gov/dnav/ng/hist/rngwhhdD.htm (accessed 30 January 2023.

48. IMO, Guidelines on the method of calculation of the attained Energy Efficiency Existing Ship Index (EEXI). Resolution MEPC.333(76), https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.333(76).pdf (accessed 10 May 2023.

49. ABS, “Energy Efficiency Existing Ship Index (EEXI),” https://ww2.eagle.org/content/dam/eagle/regulatory-news/2022/ABS%20Regulatory%20News%20-%20EEXI.pdf (accessed 10 May 2023.

50. IACS, “EEXI Implementation Guidelines,” https://iacs.org.uk/download/14308 (accessed 10 May 2023.

51. IMO, “Report of the marine environment protection committee on its sixty-second session,” http://www.crs.hr/Portals/0/MEPC%2062-24.pdf (accessed 27 October 2018).

52. J. Ahn, H. You, J. Ryu, and D. Chang, “Strategy for selecting an optimal propulsion system of a liquefied hydrogen tanker,” *Int. J. Hydrogen Energ.,* vol. 42, no. 8, pp. 5366-5380, 2017, https://doi.org/10.1016/j.ijhydene.2017.01.037.

53. N. R. Ammar, “Environmental and cost-effectiveness comparison of dual fuel propulsion options for emissions reduction onboard LNG carriers,” *Brodogradnja/Shipbuilding,* vol. 70(3), no. 3, pp. 61-77, 2019. [Online]. Available: https://hrcak.srce.hr/221116.

54. D. Dobrota, B. Lalić, and I. Komar, “Problem of boil-off in LNG supply chain,” *Transactions on Maritime Science,* vol. 2, pp. 91-100, 2013.

55. J. Blazquez, R. Fuentes, and B. Manzano, “On some economic principles of the energy transition,” *Energy Policy,* vol. 147, p. 111807, 2020, https://doi.org/10.1016/j.enpol.2020.111807.

56. D. Lukić *et al.*, “Manufacturing cost estimation in the conceptual process planning,” *Machine Design,* vol. 8, pp. 83-90, 2016.

57. Ihsan, “The analysis of the effect of indirect costs on the performance of construction project implementation,” *Jurnal PenSil,* vol. 12, pp. 100-119, 2023, doi: 10.21009/jpensil.v12i1.30978.

58. N. R. Ammar and I. S. Seddiek, “An environmental and economic analysis of emission reduction strategies for container ships with emphasis on the improved energy efficiency indexes,” *Environ. Sci. Pollut. R.,* vol. 27, no. 18, pp. 23342-23355, 2020, doi: 10.1007/s11356-020-08861-7.

59. N. R. Ammar and I. S. Seddiek, “Evaluation of the environmental and economic impacts of electric propulsion systems onboard ships: case study passenger vessel,” *Environ. Sci. Pollut. R.,* vol. 28, no. 28, pp. 37851-37866, 2021, doi: 10.1007/s11356-021-13271-4.

60. P. Thoft-Christensen, “Infrastructures and life-cycle cost-benefit analysis,” *Structure and Infrastructure Engineering,* vol. 8, no. 5, pp. 507-516, 2012, doi: 10.1080/15732479.2010.539070.