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Hybrid and Alternative Fuel Power Management Systems in Ships - Multi-Criteria Decision-Making Assessment

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ABSTRACT

This paper addresses the maritime industry's imperative to cut greenhouse gas emissions by exploring hybrid propulsion systems for bulk carrier vessels, specifically focusing on battery systems and hybridized conventional four-stroke generator engines. Utilizing the Analytic Hierarchy Process (AHP) and MARCOS decision-making method, the study evaluates diverse factors, including capital and operational expenditures, risk, emissions, bunkering availability, and weight. The research delves into different power management system topologies, such as conventional diesel engines, ammonia, and methanol-fueled engines, along with battery hybrids. The study underscores the methodological significance of decision-making tools and anticipates that evolving regulations will drive the maritime industry towards carbon neutrality through hybrid power management systems.

KEY WORDS

Decarbonization; Multi-Criteria Decision-Making (MCDM); Hybrid Propulsion System; Alternative Fuel; Analytic Hierarchy Process (AHP).

INTRODUCTION

The shipping industry has been a significant contributor to global carbon dioxide (CO2) emissions, with recent estimates indicating a 4.6% increase to 833 million tonnes in 2022 compared to 794 million tonnes in 2020 (Richardson, 2022). This rise is attributed to the combustion of approximately 203 million tonnes of fuel, primarily sourced from environmentally unfriendly fossil fuels. In response to this environmental challenge, the International Maritime Organisation (IMO) has introduced regulations under the International Convention for the Prevention of Marine Pollution (MARPOL 73/78) Annex IV as part of its decarbonization strategy (IMO, 2018). The IMO's overarching goal is to reduce annual absolute greenhouse gas (GHG) emissions from international shipping by at least 50% by 2050, compared to 2008 levels (Seddiek & Ammar, 2023). Additionally, there is a concerted effort to completely eliminate GHG emissions from the shipping industry within this century. To achieve these objectives, the IMO aims to decrease the carbon intensity emissions of global maritime transport by a minimum of 40% by 2030 and a further reduction of 70% by 2050, relative to the baseline year of 2008 (Ammar & Seddiek, 2017; IMO. 2021).
Given the prolonged lifespan of vessels, achieving these targets necessitates significant modifications to the existing fleet. Current strategies employed by the maritime sector for emission mitigation include the adoption of emissions abatement technologies, the use of marine alternative fuels, and the potential implementation of hybrid power systems (HPS) (Inal et al., 2022). This study specifically explores the use of batteries and alternative fuels such as ammonia and methanol in the power supply system of large ocean-going vessels. Advancements in battery technology, extending beyond consumer electronics and

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automobiles, have prompted consideration of their application in the maritime sector. The paper delves into the energy consumption and power demands of large ocean-going merchant vessels, exploring the feasibility of incorporating batteries into the electric grid system. This integration is identified as an area where batteries and hybridization can offer significant benefits, especially as forthcoming carbon-neutral fuels are expected to incur higher costs (MAN Energy Solutions, 2019).
Minimization of fuel consumption and reduction of emissions is one of the main objectives for designing the future generation of ship (Dedes et al., 2012). The development of hybrid vehicles, encompassing both terrestrial and marine applications, has emerged as a widely researched and implemented strategy to mitigate pollution within the transport sector (Chan et al., 2010). There are numerous advantages associated with the utilisation of electric hybrid systems in comparison to internal combustion engines, which pertain to both environmental and engineering considerations (Nazemian et al., 2024). The primary sources of air pollution from ships are NOx, CO2, SO2, and particulate matter. These emissions are generated either through direct combustion or as a result of chemical reactions occurring in the atmosphere. As a consequence of this, the implementation of hybrid electrical systems enables a significant decrease in pollutant emissions, as well as a substantial reduction in noise pollution (Padolecchia et al., 2023). In this context, it is imperative to thoroughly analyse power generation and power storage alternatives to identify more efficient solutions. In order to achieve an optimal and sustainable design that aligns with the ship's operation profile. Therefore, the existing scholarly literature predominantly emphasises the utilisation of batteries, supercapacitors, and flywheels as electric storage devices in conjunction with internal combustion engines and fuel cells as power generators when discussing hybridization technologies for ships (Geertsma et al., 2017; Nuchturee et al., 2020).
Batteries are the dominant energy storage technology due to their superior energy density, cost-effectiveness, and extensive knowledge in various transportation sectors. They consist of electrodes, electrolytes, and separators, with performance influenced by electrode material properties (Meng et al., 2017). The selection of battery type is crucial in the maritime industry, as there are various commercially available batteries suitable for transportation. Li-ion batteries are currently preferred due to their high energy densities and extended lifetimes, which are attributed to their industrial maturity and widespread availability. Despite the potential emergence of alternative technologies, lithium-ion batteries remain the preferred choice for shipping purposes (EMSA, 2022). Study by (Geertsma et al., 2017) examines the impact of a hybrid battery-diesel electric power management system on exhaust gas emissions within the global dry bulk carrier fleet. For more information, the comparison of different types of batteries is presented in the table below.

Table 1: Properties of different popular battery types. (Inal et al., 2022)

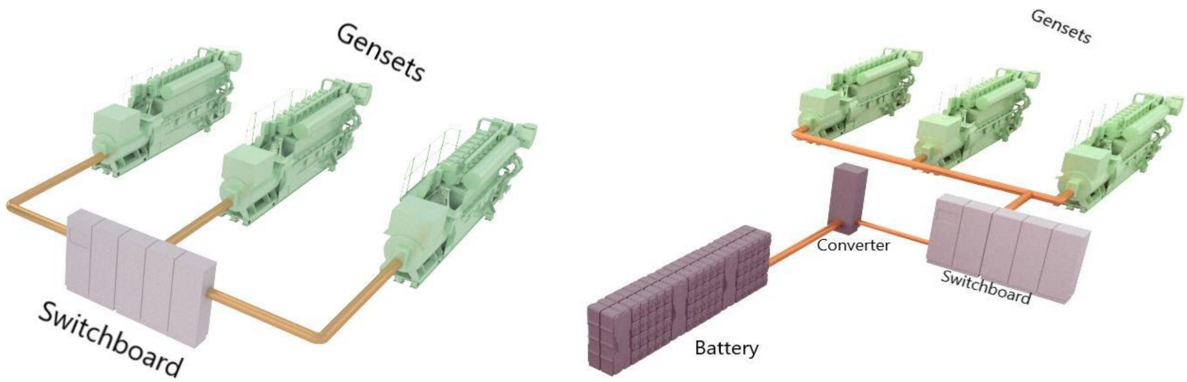
Battery type	Energy density (kWh/kg)	Power density (kW/kg)	Efficiency	Lifetime(cycle)	Capital Cost($/kWh)
Lead-Acid	$30\text{-}50 * 10^{-3}$	$75\text{-}300 * 10^{-3}$	70-90%	500-1000	70
Nickel-cadmium	$50\text{-}75 * 10^{-3}$	$150\text{-}300 * 10^{-3}$	60-65%	2000-2500	300
Nickel Metal Hydride	$60\text{-}100 * 10^{-3}$	$200\text{-}1500 * 10^{-3}$	65-90%	750	300-500
Lithium-ion	$100\text{-}200 * 10^{-3}$	$80\text{-}2000 * 10^{-3}$	85-90%	600-2000	200-700

The duration for which the battery must provide power is contingent upon the anticipated duration of unforeseen operational interruptions of the auxiliary engine. Based on empirical evidence, a battery's 15-minute duration of operation is sufficient for preventing power outages, restarting a malfunctioning auxiliary engine, and achieving optimal power output. In this particular scenario, the battery system is not to be taken as substitute for auxiliary engines, but rather as an additional system. The optimal approach, in terms of both reliability and cost-effectiveness, would involve the implementation of a solution that enables a six-hour battery operation. This duration is assumed to be adequate for resolving any potential concerns related to the auxiliary engine. The implementation of an extended battery backup system guarantees the ability to restart and restore the auxiliary engine in the event of a significant failure, thereby ensuring uninterrupted operations. Additionally, it affords maintenance personnel a sufficient duration to identify and rectify the underlying cause of the problem, thereby reducing the likelihood of a reoccurrence. Moreover, an extended battery lifespan mitigates the necessity for prompt repairs or replacements, resulting in time and resource conservation. By implementing this solution, vessel management can attain a sense of assurance, as they can be confident that their supplementary engines are adequately supported and equipped to efficiently manage unforeseen periods of inactivity. Herein, different Power Management systems with different configurations of battery hybridization and alternative fuel (Ammonia and Methanol) will be analyzed and evaluated based on decision-making process.
Ammonia and methanol are regarded as viable alternative fuels and are duly acknowledged in various power management systems. Ammonia and methanol are widely recognized as the primary candidates for alternative fuel sources, both presently and in the foreseeable future. Accordingly, different power management systems (PMS) of ship propulsion will be evaluated in this paper by combination of Conventional, Ammonia, and Methanol fuels. When evaluating each alternative fuel, the following factors are taken into account, including capital expenditures (CAPEX), risk assessment, emissions, operating

expenditures (OPEX), availability, bunkering infrastructure, and weight considerations. Various combinations of conventional fuel, alternative fuel, and hybrid systems are being considered, which are explained as follows:

1. **PMS1**: Conventional Fuel ICE.
2. **PMS2**: Conventional fuel ICE + Battery
3. **PMS3**: Ammonia ICE
4. **PMS4**: Ammonia ICE + Battery
5. **PMS5**: Methanol ICE
6. **PMS6**: Methanol ICE + Battery

This paper discusses two various combinations of ship power supply systems Traditional diesel- Mechanic propulsion (Fig.1 (a)) and semi-hybrid diesel mechanic propulsion (Fig.1 (b)).



(a) (b)

Figure 1: (a) Conventional diesel-mechanic propulsion system, (b) Semi-hybrid diesel mechanic propulsion system (Latarche, 2021)

METHODOLOGY

The goal of this paper is to assess compare and contrast various power management systems (PMS) utilised in maritime vessels, considering multiple criteria including capital expenditure (CAPEX), risk, emissions, operational expenditure (OPEX), availability, and weight. The objective of this study is to offer a thorough examination that can inform decision-making within the maritime sector, specifically in the selection of the most suitable PMS for a particular application of vessel. Accordingly, the study has been conducted regarding the following **steps**:

S1. Evaluate Different PMS: This aims to evaluate the operational efficiency and effectiveness of different power management systems (PMS) including conventional diesel engines, diesel engine-battery hybrids, ammonia ICEs, ammonia ICE-battery hybrids, methanol ICEs, and methanol ICE-battery hybrids.

S2. Assess Criteria: This analysis will evaluate the primary factors to consider when choosing a PMS, encompassing the initial capital expenditure (CAPEX), risk assessment through the implementation of Failure Modes, Effects, and Criticality Analysis (FMECA), emissions quantified in terms of CO2 equivalents, ongoing operational expenses (OPEX), availability contingent upon fuel type and bunkering accessibility, and weight considerations.

S3. Dedicated Calculations: Conduct meticulous calculations for each criterion in order to determine a score for each PMS and subsequently establish a ranking based on these scores.

S4. Apply Analytic Hierarchy Process (AHP) and MARCOS method: Utilize the methodology known as AHP to rank the various PMS separately based on survey conduction, taking into consideration the relative relevance of each criterion. Furthermore, a dedicated calculation will be carried out using the MARCOS method on criteria and alternatives.

S5. Compare and Contrast: Compare the rankings derived from the dedicated calculations of MARCOS and the AHP to comprehend the effect of utilizing distinct evaluation techniques.

S6. Provide Recommendations: Based on the analysis, suggest to the maritime industry the most appropriate PMS for various scenarios, considering the vessel's specific requirements and constraints.

The composition of each system in EMS power plant varies with some systems employing conventional fuels, alternative fuels and hybrid configurations. Following is a summary of the six PMS systems currently under consideration:

PMS1: Conventional Fuel Internal Combustion Engine (ICE): This system uses conventional fuels such as LSMGO to generate power via an internal combustion engine. Currently, this is the most widely used PMS in the shipping industry.

PMS2: Conventional Fuel ICE + Battery: This system integrates a conventional fuel (LSMGO) internal combustion engine with a battery energy storage system. The hybrid nature of this system improves fuel economy, as the battery can store excess energy and provide additional power when required.

PMS3: This system uses ammonia as an internal combustion engine's fuel source and LSMGO as the pilot fuel.

PMS4: This system is a hybrid of an internal combustion engine powered by ammonia and LSMGO as pilot fuel with a battery storage system.
PMS5: This system employs methanol as an internal combustion engine's main fuel source and LSMGO as pilot fuel.
PMS6: This hybrid system combines an internal combustion engine fueled by methanol and LSMGO as pilot fuel with a battery storage system.
A typical configuration for an auxiliary system includes a minimum of 3 auxiliary engines. 2 engines are operating in modest loads, with another engine on standby while manoeuvring or cargo loading and unloading operations where blackouts must be avoided. This configuration permits an unexpected shutdown of one of the engines. During sailing in deep sea, 1 auxiliary engine is capable of supplying the load, the second is set to get started, and the third is undergoing maintenance. PMS1, PM3, and PMS5 do not have hybrid battery systems. These three systems are evaluated for use in important port operations with the configuration described. So, PMS1,3, and 5 will each have three engines, with two of them operating at 40% load simultaneously (Fig.2).

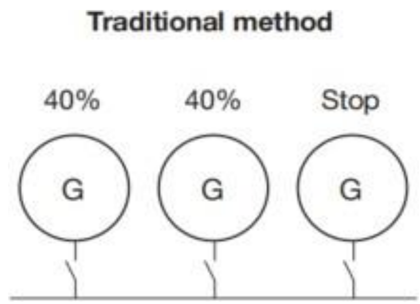


Figure 2: Traditional method

When two or more than two auxiliary engines operate at a low capacity for safety grounds, a battery has a substantial potential for savings. It can be used to mitigate sudden engine shutdowns and unforeseen events. Also, it has the capability to enhance the fuel efficiency of the auxiliary engines by selectively operating a single engine at elevated loads. The result leads to an enhancement in productivity while simultaneously decreasing operating expenses as well as repair costs. PMS 2, PMS 4, and PMS 6 have battery-hybrid systems, so in these three systems there will be two auxiliary engines, one operating at 80% capacity, second one in stop condition and battery (Fig.3).

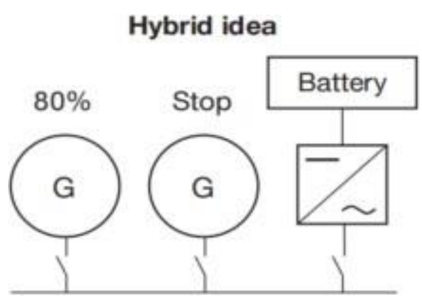


Figure 3: Hybrid Idea

Data collection of PMS scenarios for a Bulk Carrier

This study utilised data obtained from a variety of sources. This includes manufacturer data, data found in the literature, and data calculated based on established engineering principles. This section describes the methodologies used to collect data for each PMS system criterion. The ICE engines used for this study are shown in Table 2.

Table 2: Generator engine data (EMSA, 2022; Wärtsilä, 2023)

Power management system	Auxiliary engine	SFOC - g/kWh	Engine cost - USD/kW	Engine O&M cost USD/kW
PMS1, PMS2	Wartsila 6L25 auxiliary engine. 6-cylinder 2040kw ,900rprm	At 40% load - 198.2 At 80% load - 186.1	230	5

PMS2, PMS3, PMS4, PMS5	Wartsila 6L5DF Dual fuel Auxiliary engine, 6-cylinder 1890kW,900rpm	At 40% load - 202.1 At 80% load - 190.6	550	5.2

In both scenarios, total electric power is assumed to be 1480 kW, demanding 1560 kW from the auxiliary engine under the assumption that the generator is 95% efficient. The hotel load is assumed constant at the 560-kW required at port for operation. And the remaining power is required for port-critical activities, mainly the operation of cranes or bunker and ballast systems. In both scenarios, it is anticipated that the PMS will be operational for 1000 hours per year. For 6 hours of continuous operation in a hybrid system, the battery capacity required is 4230 kWh at a c-rate of 0.35. The Specific price of the battery in the system is taken at 500 USD/kWh, and the O&M cost is taken at 10 USD/kW (MAN Energy Solutions, 2019). Inverter installation is essential in Hybrid operation for the DC-AC conversion from the battery. The average inverter cost is 813 USD/kW (Brinsmead et al., 2015).

PMS3,4,5,6 is powered by a Wärtsilä 9L25DF engine. According to the manufacturer, this engine is already capable of running on multiple fuels and can therefore be readily upgraded to operate on future fuels like ammonia and methanol. In addition, the ratio considered for this study was influenced by Wartsila's announcement that their engine was effectively tested in full-scale operation with a blend of LSMGO (Wärtsilä, 2021).

For PMS3 and PMS 4 Fuel oil blend is: (Wärtsilä, 2021)

- GAS -> Ammonia - 70%
- Pilot fuel -> LSMGO - 30%

According to (Latarche, 2021) methanol exhibits a low ignitability when used as a fuel for internal combustion engines (ICE), as evidenced by its high ignition temperature of 470℃. Consequently, in order to ensure a consistent and stable combustion process as well as optimal engine performance, it is necessary to introduce 5% of pilot fuel, specifically LSMGO, into the combustion chamber. For PMS 5 and PMS 6 fuel oil blend is:

- GAS -> Methanol - 95%
- Pilot fuel -> LSMGO - 5%

Selective catalytic Reduction (SCR) is used as the after-treatment system for Ammonia powered PMS3 and PMS4.SCR Cost is taken 133USD/kW (EMSA, 2022).

Calculation and Assessment of evaluation criteria

This section will elucidate the process employed for calculating and assessing the evaluation criteria. Six power plant systems of bulk carrier ship will be evaluated based on the following criteria: capital expenditure (CAPEX), operational expenditure (OPEX), risk profile, availability/bunkering, weight, and emissions. Each criterion will be assigned a weighting based on its significance to the overall performance and feasibility of the system using AHP analysis.

CAPEX- Capital Expenditure

The capital expenditure (CAPEX) of a ship encompasses multiple components, which encompass the expenses related to the ship's asset acquisition and the financial costs associated with ship financing. In the context of ship-owners, CAPEX is typically regarded as a crucial cost component alongside OPEX within the financial statements. Numerous components, including the engine, aftertreatment system, storage tanks, and fuel supply system (FSS), are included in the fixed costs of a newly constructed vessel. The expenses incurred are not contingent upon the frequency and intensity of vessel utilization (EMSA, 2022). For the CAPEX, the cost of the engine, after-treatment system, battery, and inverter is taken into consideration as per the requirements of the PMS system.

PMS1:
CAPEX = Engine cost = 1,407,600USD

PMS2:
CAPEX= Engine cost + Battery cost + Inverter cost = 3,626,565 USD

PMS3:
CAPEX= Engine cost + SCR cost = 3,872,610 USD

PMS4:
CAPEX = Engine cost + SCR cost + Battery cost + Inverter cost = 5,269,905 USD

PMS5:
CAPEX = Engine cost = 3,118,500 USD

PMS6:
CAPEX= Engine cost + Battery cost + Inverter cost = 4,767,165 USD

OPEX- Operational Expenditure

Operational expenditures (OPEX) encompass variable costs that are based upon the utilisation of the vessel. These costs primarily include fuel expenses, bunkering charges, maintenance, and repair costs. The daily capital and operating cost per vessel are influenced by several factors, such as crew, ship size, insurance policy, and maintenance. Several factors have been identified as influential when making investments. These factors encompass fuel prices, the geographical area in which operations are conducted, relevant regulations, the duration of time at sea, and the lifespan of the vessel (Olaniyi et al., 2018). In addition, the weather and environmental conditions encountered by a maritime vessel can have a substantial influence on its operational costs. For instance, inclement weather conditions can potentially require the consumption of extra fuel or give rise to enhanced vessel deterioration, thereby resulting in added maintenance expenses (Olaniyi et al., 2018). For the OPEX Engine O&M, Battery O&M, SCR O&M, and fuel cost are taken into consideration. Fuel cost calculations are expressed below:
Global average cost of LSMGO Fuel is 840USD/Tonne (*Rotterdam Bunker Prices*, 2023);
Fuel Cost Ammonia = 650USD/Tonne (EMSA, 2022);
Fuel Cost Methanol = 350USD/Tonne (Korberg et al., 2021)

PMS1:

$$Fuel\ consumption\ at\ 40\%\ load\ =\ FC_{LSMGOonly}\ =\ SFOC\ *\ Load\ (40\%) *\ RunningHours, =\ 1560 * 198.2 * 1000 * 10^{-6}\ =\ 309.19\ tonnes\ \ , \text{Zincir, 2022.} \quad [1]$$

$$OPEX\ =\ (FC_{LSMGO}\ \times\ Fuel\ Cost)\ +\ Engine\ O\&M\ =\ 259{,}721.28\ USD \quad [2]$$

PMS2:

$$Fuel\ consumption\ at\ 80\%\ load\ =\ SFOC\ *\ Load\ (40\%)\ *\ RunningHours\ =\ 1560 * 186.1 * 1000 * 10^{-6} =\ 290.316\ tonnes \quad [3]$$

$$OPEX\ =\ (FC_{LSMGO} \times\ Fuel\ Cost_{LSMGO}\ )\ +\ Engine\ +\ Battery\ O\&M\ =\ 271{,}315\ USD \quad [4]$$

PMS3:

$$FC_{LSMGOonly}\ =\ SFOC\ *\ P_{design}\ *\ Load\ *\ RunningHours \quad [5]$$

$$FR_{ammonia} = \frac{M_{ammonia} * LHV_{ammonia}}{M_{ammonia} * LHV_{ammonia} + M_{LSMGO} *\ LHV_{LSMGO}} \quad [6]$$

$$M_{LSMGO}\ *\ LHV_{LSMGO}\ =\ FR_{ammonia}\ *\ M_{ammonia}\ *\ LHV_{ammonia}\ +\ FR_{LSMGO}\ *\ M_{LSMGO}\ *\ LHV_{LSMGO} \quad [7]$$

Equation (5) can be used to calculate the fuel consumption of a single engine that runs solely on LSMGO for 1000 hours:

$$FC_{LSMGOonly}\ =\ 202.1(g/kWh)\ * (780 * 2)\ (kW)\ *\ 1000\ hours\ * 10^{-6} =\ 315\ tonnes \quad [8]$$

$FR_{ammonia}$	70%
$LHV_{ammonia}$(MJ/kg)	18.5
FR_{LSMGO}	30%
LHV_{LSMGO}(MJ/kg)	43.5

Fuel Ratios & LHV of Ammonia and LSMGO (Huang et al., 2022; Zincir, 2022).
Given that the FR_{LSMGO} = 0.3, Equation (6) can be used to determine the ratio between the mass in tonnes consumed by ammonia ($M_{ammonia}$) and the mass in tonnes consumed by LSMGO (M_{LSMGO}). In the instance of our engine, which burns 70% NH3 and 30% LSMGO as pilot fuel, the MLSMGO can be calculated as:

$$FC_{LSMGOonly} * FR_{LSMGO}\ =\ 315\ *\ 0.3\ =\ 95\ tonnes. \quad [\ 9\ ]$$

$$M_{ammonia}\ =\ 5.486\ *\ M_{LSMGO}\ =\ 5.486\ *\ 95\ =\ 521\ tonnes \quad [10]$$

As a result, the fuel consumption for 1000 hours of main engine operation was discovered to be:

- For 1000 hours of operation, 521 tonnes of NH3 are used.

- Which requires 95 tonnes of LSMGO (as pilot fuel).

$$OPEX = (FC_{LSMGO} \times Fuel\ Cost_{LSMGO}) + (FC_{Ammonia} \times Fuel\ Cost_{Ammonia}) + Engine\ O\&M\ Cost + SCR\ O\&M\ Cost = 453{,}577.4\ USD \quad [11]$$

PMS4:
Similar to Eqs (5-7) of the previous configuration for 1000 hrs operation:

$$FC_{LSMGOonly} = 190.6(g/kWh) * (1560)(kW) * 1000\ hours * 10^{-6} = 297\ tonnes \quad [12]$$

Given that the $FR_{LSMGO} = 0.3$, Equation (6) can be used to determine the ratio between the mass in tonnes consumed by ammonia ($M_{ammonia}$) and the mass in tonnes consumed by LSMGO (M_{LSMGO}).
In the instance of our engine, which burns 70% NH3 and 30% LSMGO as pilot fuel, the MLSMGO can be calculated according to Eq (13). The ammonia consumption mass in tonne can subsequently be calculated 89 tonnes, which takes into account the various fuel ratios.

$$FC_{LSMGOonly} * FR_{LSMGO} = 297 * 0.3 = 89\ tonnes. \quad [13]$$

$$M_{ammonia} = 5.486 * M_{LSMGO} = 5.486 * 89 = 489\ tonnes \quad [14]$$

As a result, the fuel consumption for 1000 hours of main engine operation was discovered to be 489 tonnes of NH3. Which requires 89 tonnes of LSMGO (as pilot fuel).

$$OPEX = (FC_{LSMGO} \times Fuel\ Cost_{LSMGO}) + (FC_{Ammonia} \times Fuel\ Cost_{Ammonia}) + Engine\ O\&M\ Cost + SCR\ O\&M\ Cost + Battery\ O\&M\ Cost = 424{,}629.8\ USD \quad [15]$$

PMS5:
Similar to Eqs (5-7) by changing the fuel from Ammonia to methanol:

$$FC_{LSMGOonly} = SFOC * P_{design} * Load * RunningHours \quad [16]$$

$$FR_{methanol} = \frac{M_{methanol} * LHV_{methanol}}{M_{methanol} * LHV_{methanol} + M_{LSMGO} * LHV_{LSMGO}} \quad [17]$$

$$M_{LSMGO} * LHV_{LSMGO} = FR_{methanol} * M_{methanol} * LHV_{methanol} + FR_{LSMGO} * M_{LSMGO} * LHV_{LSMGO} \quad [18]$$

Equation (18) can be used to calculate the fuel consumption of a single engine that runs solely on LSMGO for 1000 hours:

$$FC_{LSMGOonly} = 202.1(g/kWh) * (1560)(kW) * 1000\ hours * 10^{-6} = 315\ tonnes \quad [19]$$

FRmethanol	95%
LHVmethanol(MJ/kg)	19.9
FRLSMGO	5%
LHVLSMGO(MJ/kg)	43.5

Fuel Ratios & LHV of Methanol and LSMGO.
Given that the $FR_{LSMGO} = 0.3$, Equation (6) can be used to determine the ratio between the mass in tonnes consumed by Methanol ($M_{methanol}$) and the mass in tonnes consumed by LSMGO (M_{LSMGO}). In the instance of our engine, which burns 95% Methanol and 5% LSMGO as pilot fuel, the M_{LSMGO} can be calculated by Eq (20). The methanol consumption mass in tonne can subsequently be calculated using Equation (21), which takes into account the various fuel ratios.

$$FC_{LSMGOonly} * FR_{LSMGO} = 315 * 0.05 = 15.76\ tonnes. \quad [20]$$

$$M_{methanol} = 41.53 * M_{LSMGO} = 41.53 * 15.76 = 654.6\ tonnes \quad [21]$$

As a result, the fuel consumption for 1000 hours of main engine operation was discovered to be 654.6 tonnes of methanol usage. Which requires 15.76 tonnes of LSMGO (as pilot fuel).

$$OPEX = (FC_{LSMGO} \times Fuel\ Cost_{LSMGO}) + (FC_{Methanol} \times Fuel\ Cost_{Methanol}) + Engine\ O\&M\ Cost = 271860.3\ USD \quad [22]$$

PMS6:

Similar to Eqs (5-7) from the previous configuration, Eq (5) can be used to calculate the fuel consumption of a single engine that runs solely on LSMGO for 1000 hours:

$$FC_{LSMGOonly} = 190.6(g/kWh) * (1560)\ (kW) * 1000\ hours * 10^{-6} = 297\ tonnes \quad [23]$$

Given that the FRLSMGO = 0.3, Equation (2) can be used to determine the ratio between the mass in tonnes consumed by Methanol ($M_{methanol}$) and the mass in tonnes consumed by LSMGO (M_{LSMGO}). In the instance of our engine, which burns 95% Methanol and 5% LSMGO as pilot fuel, the MLSMGO can be calculated in Eq (24). The methanol consumption mass in tonne can subsequently be calculated using Equation (25), which takes into account the various fuel ratios.

$$FC_{LSMGOonly} * FR_{LSMGO} = 297 * 0.05 = 14.85\ tonnes. \quad [24]$$

$$M_{methanol} = 41.53 * M_{LSMGO} = 41.53 * 14.85 = 614.6\ tonnes \quad [25]$$

As a result, the fuel consumption for 1000 hours of main engine operation was discovered to be:

- For 1000 hours of operation, 614.6 tonnes of methanol are used.
- Which requires 14.85 tonnes of LSMGO (as pilot fuel).

$$OPEX = (FC_{LSMGO} \times Fuel\ Cost_{LSMGO}) + (FC_{\ Methanol} \times Fuel\ Cost_{Methanol}) + Engine\ O\&M\ Cost + Battery\ O\&M\ Cost = 255{,}290.48\ USD \quad [26]$$

Emissions

This study will evaluate the GHG emission of each PMS in a Tank to wake perspective, fueled by numerous fuels, including LSMGO, methanol, and ammonia. This investigation examined carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O), the three most important greenhouse gas emissions. After carbon dioxide, CH4 is the second largest contributor to greenhouse gas emissions. The vast majority of CO2 emissions result from the combustion of fuels, while a negligible amount is emitted during processing. The three primary sources of CH4 emissions were vented, furtive, and unburned emissions. Except for engines powered by ammonia, the contribution of N2O is minimal. Here, the greenhouse gas emissions are expressed in tonnes of CO2 equivalent (CO2eq), which is shown in Table 3. The following IPCC AR5 characterization parameters were used to calculate GHG emissions in order to evaluate the warming potential over the next hundred years: 1 for CO2, 28 for CH4, and 265 for N2O (IPCC, 2023).

$$Ef(GHG) = Ef(CO2) + 28 \times Ef(CH4) + 265 \times Ef(N2O) \quad [27]$$

For a medium-speed 4-stroke AE engine with:

LSMGO:

$$Ef(GHG) = 3.21 + (28 \times 5.35 \times 10^{-5}) + (265 \times 1.60 \times 10^{-4}) = 3.25\ \frac{ton\ CO2 - eq}{ton\ fuel} \quad [28]$$

Ammonia:

$$Ef(GHG) = 0 + (28 \times 0) + (265 \times 5.02 \times 10^{-3}) = 1.33\ \frac{ton\ CO2 - eq}{ton\ fuel} \quad [29]$$

Methanol:

$$Ef(GHG) = 1.38 + (28 \times 2.53 \times 10^{-5}) + (265 \times 7.59 \times 10^{-6}) = 1.38\ \frac{ton\ CO2 - eq}{ton\ fuel} \quad [30]$$

Table 3: The engines' CO2 equivalent emission factors (tons/tons of fuel) (Huang et al., 2022)**.**

Fuel	CO2	CH4	N2O	Total (CO2-eq)
LSMGO	3.21	5.35×10^{-5}	1.60×10^{-4}	3.25
Ammonia	0	0	5.02×10^{-3}	1.33
Methanol	1.38	2.53×10^{-5}	7.59×10^{-6}	1.38

In our investigation of ammonia ICE and hybrid ammonia + diesel ICE, SCR is utilized to reduce N2O emissions. We assume that the SCR will contribute to a 70 percent reduction.

Table 4: NOx Emission factor

	Emission factor
N2O emission without SCR	1.33
N2O emission with SCR- 70% reduction	0.399

Consequently, the TTW Annual GHG Emissions have been estimated by multiplying the fuel consumptions for each scenario and shown in Table 5:

Table 5 Emissions of each PMS

Emissions (Ton CO2-eq)	Conventional Diesel engine	Diesel- Hybrid battery	Ammonia ICE engine	Ammonia + Diesel ICE-Hybrid	Methanol ICE	Methanol ICE+ Hybrid
	1005	944	514	485	955	900

Risk

A Failure Mode, Effects, and Criticality Analysis (FMECA) was performed in order to assess the risk of using different PMS onboard. For numerically evaluating each hazard and ranking the risk, the Risk Priority Number (RPN) indicator with the following formula has been utilised:

$$RPN = S \times P \times E \qquad [31]$$

S = Severity, P = Probability, E = Ease of detection
After calculating the RPN values, a Threshold has been implemented to appropriately classify each hazard:

- Green colour, if <100 - Low risk hazard
- Yellow colour, if 100 ≤ medium risk hazard <180
- Red colour, if high risk hazard ≥ 180

For each system, potential failure modes in numerous components are identified. Here is an executive summary:

- All six systems share certain components, such as the engine (though the type of fuel varies), the alternator, the power management system, and the LSMGO bunkering procedure, and consequently share similar failure modes in these components.
- The fuel systems and safety systems differ based on whether the fuel is conventional, ammonia, or methanol, and each has its own failure mechanisms. For example, ammonia systems are susceptible to failures associated with nitrogen supply and leak detection, whereas methanol systems are susceptible to methanol pump failure or injector obstruction.
- The systems incorporating batteries, namely PMS2, PMS4, and PMS6, are equipped with supplementary components, namely the battery itself and the battery management system. These components possess essential dangers, including but not limited to battery overheating or thermal runaway, short circuit occurrences, cell degradation, and sensor malfunctions.
- It is important to note that the act of bunkering introduces various potential failure modes in all systems, and the specific nature of these failures is contingent upon the type of fuel being bunkered.

FMECA analysis for each PMS is done and the results obtained is as shown in the following risk plot.

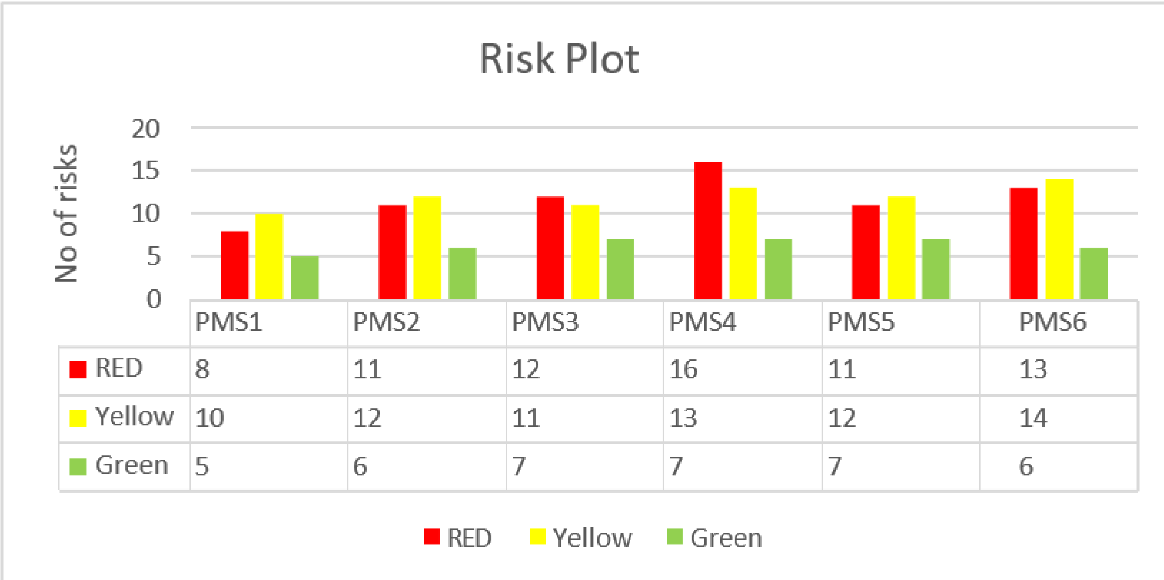


Figure 4: Risk plot from FMECA

Availability / Bunkering

The research conducted an examination of thirteen prominent international ports to determine the presence of various marine fuel options and shore-side battery charging (SBC) infrastructure. The ports were strategically chosen from three regions, namely Europe, Asia, and the Americas, with each region providing a total of five ports. The marine fuel options under consideration encompassed LSMGO, Ammonia, and Methanol. The findings revealed that LSMGO was widely accessible, as it was found to be offered in all thirteen ports. The widespread use of LSMGO as a primary marine fuel in various maritime operations is evident from its ubiquity. Ammonia and Methanol were found to be accessible in eight out of the thirteen ports, indicating a discernible transition towards environmentally friendly fuel alternatives in certain regions of the globe. The aforementioned fuels were readily accessible at all European ports (with the exception of London) and Asian ports (excluding Mumbai), as well as in the cities of New York and Los Angeles within the Americas. Shore-side Battery Charging (SBC) facilities, which constitute a significant component of the maritime sector's transition towards electrification, were found to be accessible in seven out of the total thirteen ports. These facilities were accessible in all European ports, with the exception of London, as well as in Shanghai and Singapore in Asia, and in Los Angeles in the Americas.
One noteworthy observation pertained to the presence of comprehensive marine fuel and SBC facilities at the ports of Rotterdam, Hamburg, Antwerp, Shanghai, Singapore, and Los Angeles. In contrast, it should be noted that ports such as London, Mumbai, and Panama exclusively offered LSMGO. The provided data offers a concise overview of the present state of marine fuel accessibility and the level of preparedness for the implementation of electrification within the shipping sector. The aforementioned statement underscores the regional disparities in the implementation of alternative fuels and electrification within the maritime industry. Specifically, European and Asian ports tend to exhibit a more extensive range of marine fuels and shore-based charging SBC facilities in comparison to their American counterparts.

Weight

This study entails the calculation of weights for different configurations of PMS. To determine the weight of a specific PMS, technical specifications provided by the engine manufacturer have been studied. These specifications typically include information on the engine's weight, dimensions, power output, and other relevant details.

Table 6: Engine weight data (Wärtsilä, 2023) (Latarche, 2021).

	Wartsila 6L25	Wartsila 6L25DF
Engine Weight- in tonnes	38.3	39.6
Battery weight-system (30 kg/kWh) in tonnes	126.9	

PMS1: The present configuration employs three 6L25 engines, each weighing 38.3 metric tonnes, resulting in a cumulative engine weight of 114.9 metric tonnes.
PMS2: system achieves improved efficiency by integrating two 6L25 engines, each weighing 38.3 tonnes, along with a battery weighing 126.9 tonnes, resulting in a combined weight of 203.5 tonnes.
PMS3: system incorporates three 6L25DF engines, with each engine weighting 39.6 metric tonnes. Consequently, the total weight of the engines employed in the project amounts to 118.8 metric tonnes.
PMS4: in this configuration, combines two 6L25 engines (76.6 t) with a battery (126.9 t) to attain a total weight of 203.5 t.
PMS5: in this configuration utilises a trio of 6L25DF engines, collectively weighing 118.8 tonnes.
PMS6: this configuration utilises a hybrid PMS system consisting of two 6L25 engines weighing 76.6 tonnes each, along with a battery weighing 126.9 tonnes, resulting in a total weight of 203.5 tonnes. This weight is comparable to that of PMS2 and PMS4. The significance of the engine and battery weights in determining the overall efficiency and performance of each PMS configuration cannot be overstated. The evaluation of these weights will greatly contribute to the findings of this study

AHP method

The Analytic Hierarchy Process (AHP) will be used to rank the PMS systems based on the importance of each criterion in terms of the overall performance and feasibility of the system. Fig.5 depicts hierarchical decision-making framework of the study regarding the goal of hybrid and alternative fuel power management systems in Ships.

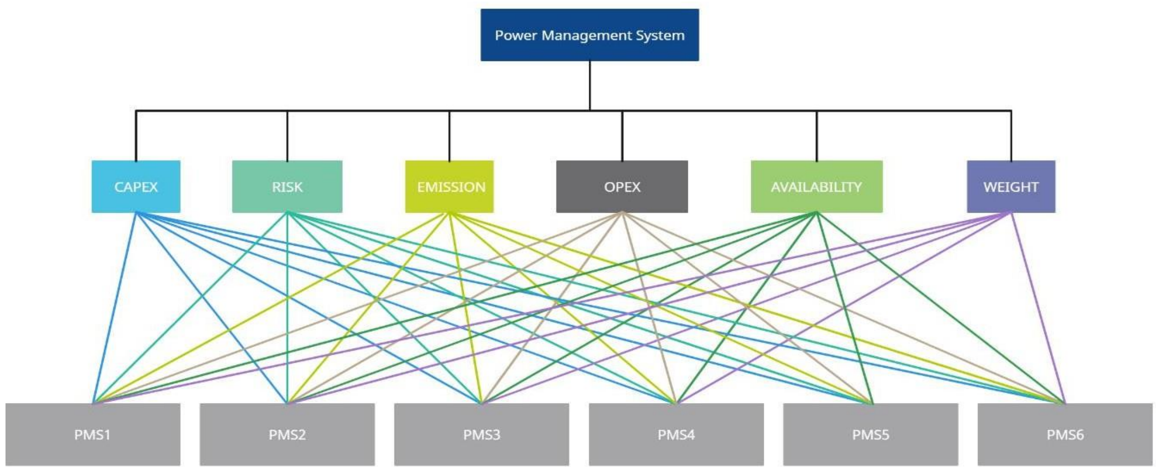


Figure 5: AHP flowchart for this study.

The research further demonstrates its practical application by employing a questionnaire to conduct surveys among identified Decision Makers (DMs). By using pairwise comparison and AHP techniques, managers can analyze many solutions based on various factors and prioritize them based on their preferences. The survey has been conducted among key stakeholders such as maritime industry, universities, technology companies, research and development (R&D) branches and etc.

Measurement of Alternatives and Ranking according to COmpromise Solution (MARCOS) method

The Measurement of Alternatives and Ranking according to MARCOS method is a decision-making technique used in multi-criteria decision analysis (MCDA). It is designed to help decision-makers evaluate and rank a set of alternatives based on multiple criteria or objectives. The MARCOS method uses a compromise solution that balances the conflicting objectives represented by the criteria. Pairwise comparison of criteria and defining the weight of each criteria have been obtained from AHP method section. The MARCOS method is performed through the following steps (Stević et al., 2020):
Step 1: Creating an initial fuzzy decision-making matrix.
Step 2: Formation of an extended initial matrix (X). In this step, the extension of the initial matrix is performed by defining the ideal (AI) and anti-ideal (AAI) solution.
Step 3: Normalization of the extended initial matrix (N).
Step 4: Determination of the weighted matrix (V). The weighted matrix V is obtained by multiplying the normalized matrix N with the weight coefficients of the criterion.
Step 5: Calculation of the utility degree of alternatives K_i.
Step 6: Determination of the utility function of alternatives $f(K_i)$.
Step 7: Ranking the alternatives based on the final values of utility functions.

The MARCOS method provides a structured approach that the best alternative is the one that is closest to the ideal and at the same time furthest from the anti-ideal reference. It aids decision-makers in identifying trade-offs and making informed choices aligned with their preferences and objectives.

RESULTS AND DISCUSSION

Survey and AHP results

The following report analyses six PMS options for ocean-going vessels: This pairwise comparison matrix in Table 7 illustrates, according to the evaluation, how each criterion (CAPEX, RISK, Emission, OPEX, Availability, and Weight) compares to each other in terms of importance. This matrix is used to determine the relative weights of the criteria, which are then used to rank the alternatives (in this case, the Power Management Systems). Priority weights are computed by normalising and then aggregating the values in each column and row.

Table 7: Pairwise comparison of criteria

	CAPEX	RISK	Emission	OPEX	Availability	Weight
CAPEX	1.00	5.00	0.20	1.00	5.00	7.00
RISK	0.20	1.00	0.20	0.33	3.00	5.00
Emission	5.00	5.00	1.00	5.00	7.00	9.00
OPEX	1.00	3.00	0.20	1.00	5.00	7.00
Availability	0.20	0.33	0.14	0.20	1.00	3.00
Weight	0.14	0.20	0.11	0.14	0.33	1.00

The resulting weights reflect the relative significance of each decision-making criterion. These weights are then used to perform a weighted evaluation of the alternatives, which ultimately results in the alternatives' final ranking. By calculating the priority vector using the pairwise comparison matrix, the priority of each alternative is determined, along with its rank. as shown in the table 8.

Table 8 Priority of each alternative

	Priority vector	Priority (%)	RANK
CAPEX	0.195	19.46	2
RISK	0.091	9.06	4
Emission	0.468	46.78	1
OPEX	0.172	17.17	3
Availability	0.049	4.89	5
Weight	0.026	2.64	6

About 47 percent of criteria preference devotes to emission reduction, which shows the most important parameter of propulsion system selection among ship operators and designers. CAPEX and OPEX are second and third rank in the survey in about equal priority. The following matrices show the alternatives for each criterion.

Table 9 Alternatives for criterion CAPEX

Alternatives	PMS1	PMS2	PMS3	PMS4	PMS5	PMS6
PMS1	1.00	5.00	5.00	9.00	3.00	7.00
PMS2	0.20	1.00	3.00	7.00	1.00	5.00

PMS3	0.20	0.33	1.00	7.00	0.33	5.00
PMS4	0.11	0.14	0.14	1.00	0.20	0.33
PMS5	0.33	1.00	3.00	5.00	1.00	5.00
PMS6	0.14	0.20	0.20	3.00	0.20	1.00

Table 10 Alternatives for criterion RISK

Alternatives	PMS1	PMS2	PMS3	PMS4	PMS5	PMS6
PMS1	1.00	3.00	3.00	9.00	5.00	7.00
PMS2	0.33	1.00	0.33	9.00	3.00	5.00
PMS3	0.33	3.00	1.00	5.00	1.00	3.00
PMS4	0.11	0.11	0.20	1.00	0.20	0.33
PMS5	0.20	0.33	1.00	5.00	1.00	3.00
PMS6	0.14	0.20	0.33	3.00	0.33	1.00

Table 11 Alternatives for criterion Emission

Alternatives	PMS1	PMS2	PMS3	PMS4	PMS5	PMS6
PMS1	1.00	0.33	0.14	0.11	0.33	0.20
PMS2	3.00	1.00	0.33	0.11	0.20	0.33
PMS3	7.00	3.00	1.00	1.00	5.00	3.00
PMS4	9.00	9.00	1.00	1.00	7.00	5.00
PMS5	3.00	5.00	0.20	0.14	1.00	0.33
PMS6	5.00	3.00	0.33	0.20	3.00	1.00

Table 12 Alternatives for criterion OPEX

Alternatives	PMS1	PMS2	PMS3	PMS4	PMS5	PMS6
PMS1	1.00	1.00	9.00	3.00	1.00	0.20
PMS2	1.00	1.00	9.00	7.00	1.00	1.00
PMS3	0.11	0.11	1.00	0.20	0.14	0.11
PMS4	0.33	0.14	5.00	1.00	0.20	0.14
PMS5	1.00	1.00	7.00	5.00	1.00	0.33
PMS6	5.00	1.00	9.00	7.00	3.00	1.00

Table 13 Alternatives for criterion Availability

Alternatives	PMS1	PMS2	PMS3	PMS4	PMS5	PMS6
PMS1	1.00	1.00	5.00	3.00	9.00	7.00
PMS2	1.00	1.00	5.00	3.00	7.00	9.00
PMS3	0.20	0.20	1.00	0.33	7.00	5.00
PMS4	0.33	0.33	3.00	1.00	5.00	7.00
PMS5	0.11	0.14	0.14	0.20	1.00	0.33
PMS6	0.14	0.11	0.20	0.14	3.00	1.00

Table 14 Alternatives for criterion Weight

Alternatives	PMS1	PMS2	PMS3	PMS4	PMS5	PMS6
PMS1	1.00	7.00	3.00	7.00	3.00	7.00
PMS2	0.14	1.00	0.20	1.00	0.20	1.00
PMS3	0.33	5.00	1.00	5.00	1.00	5.00
PMS4	0.14	1.00	0.20	1.00	0.20	1.00
PMS5	0.33	5.00	1.00	5.00	1.00	5.00
PMS6	0.14	1.00	0.20	1.00	0.20	1.00

Table 15 Mean Priorities by alternative AHP analysis

Crit./Alt.	Weight of criteria	PMS1	PMS2	PMS3	PMS4	PMS5	PMS6
CAPEX	19.46	8.64	3.51	2.32	0.54	3.52	0.93
RISK	9.06	3.76	1.77	1.70	0.25	1.08	0.49
Emission	46.78	1.42	2.76	13.41	18.68	4.35	6.17
OPEX	17.17	2.68	4.00	0.39	0.93	2.92	6.26
Availability	4.89	1.61	1.61	0.53	0.79	0.14	0.20
Weight	2.64	1.14	0.13	0.56	0.13	0.56	0.13

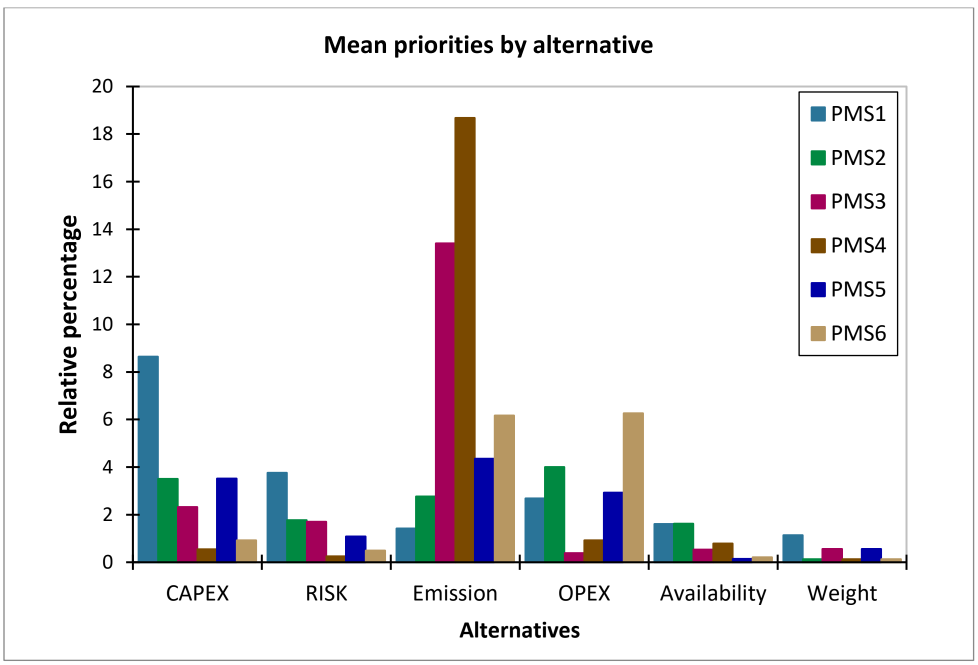


Figure 6: Mean prioritize of alternatives by percentage.

Table 16: PMS alternatives ranking.

Power system	Alt. num.	Rank
PMS1: Conventional Fuel ICE	3.259	**5**
PMS2: Conventional fuel ICE + Battery	2.903	**6**
PMS3: Ammonia ICE	6.985	**2**
PMS4: Ammonia ICE + Battery	9.068	**1**
PMS5: Methanol ICE	3.342	**4**
PMS6: Methanol ICE + Battery	4.197	**3**

According to AHP analysis results in Table 16, one may conclude hybridised system of ICE engines with battery (PMS 4) can be the best option among alternatives. The availability and cost of Ammonia as an alternative fuel make it appealing among stakeholders and can be a possible option for marine fuel in the future of the shipping industry. In the next section, another Multi-Criteria Decision-Making (MCDM) process will be carried out based on available data and dedicated calculations.

Criteria Evaluation for MARCOS Analysis

The specialised calculations provide a comprehensive evaluation of each power management system based on the values for each criterion. In the present section, these calculations are presented independently for each criterion, providing a clear overview of the performance of each PMS in each criterion. The sections that follow detail the calculations performed for each criterion. Measurement of Alternatives and Ranking according to COmpromise Solution (MARCOS) method will be applied to alternatives to rank them and compare them with AHP method.

CAPEX

Based on the cost of the systems and their installation, the CAPEX for each PMS was computed. The following are the results:

$$(If\ CAPEX = \$\ 0\ \ then\ Score = 100\ @If\ CAPEX = \$\ 8\ mil\ \ \ then\ Score = 0) \qquad [32]$$

Table 17: CAPEX Results

Alternatives	USD	Score
PMS1 (Conventional Diesel Engine)	\$1407600	82.41
PMS2 (Diesel Engine-Battery Hybrid)	\$3626565	54.67
PMS3 (Ammonia ICE)	\$3872610	51.59
PMS4 (Ammonia ICE-Battery Hybrid)	\$5269905	34.13
PMS5 (Methanol ICE)	\$3118500	61.02
PMS6 (Methanol ICE-Battery Hybrid)	\$4767165	40.41

The conventional diesel engine system, PMS1, has the lowest CAPEX, whereas the most advanced and advanced system, the ammonia ICE-battery hybrid system, PMS4, has the highest CAPEX. The remaining systems range between these two extremes.

RISK

Calculated using Failure Modes, Effects, and Criticality Analysis (FMECA), The risk values for each PMS are as follows:
To determine these normalised values, all RPN for each FMECA analysis are added together. The PMS1 had the lowest risk score, with a value of 3,459. This was likely due to its long-standing use and continuous improvements. The PMS4, received the maximum risk score of 5816. The risk scores for the remaining systems, PMS2, PMS3, PMS5, and PMS6, were 4456, 4735, 4604, and 5195, respectively, due to the incorporation of alternative fuels and hybrid technologies. Comparing these risk scores assists in determining the tradeoffs involved in selecting an appropriate PMS for ocean-going vessels.

Table 18: Risk Results (Total of RPN values)

Alternatives	RISK	Score
PMS1 (Conventional Diesel Engine)	3459	50.59
PMS2 (Diesel Engine-Battery Hybrid)	4456	36.35
PMS3 (Ammonia ICE)	4735	32.36
PMS4 (Ammonia ICE-Battery Hybrid)	5816	16.92
PMS5 (Methanol ICE)	4604	34.23
PMS6 (Methanol ICE-Battery Hybrid)	5195	25.79

Conditions considered,

$$(If\ RISK = 1\ then\ Score = 100@If\ RISK = 7000\ \ then\ Score = 0) \quad [33]$$

Table 19: Risk analysis

	High	Medium	Low	
	RED	Yellow	Green	Total
PMS1	8	10	5	23
PMS2	11	12	6	29
PMS3	12	11	7	30
PMS4	16	13	7	36
PMS5	11	12	7	30
PMS6	13	14	6	33

Emission

These are the calculated emission values for every PMS in terms of carbon dioxide equivalents (CO2 eq):

Table 20 Emissions Results

Alternatives	Emission	Score
PMS1 (Conventional Diesel Engine)	1004	16.26
PMS2 (Diesel Engine-Battery Hybrid)	943	21.37
PMS3 (Ammonia ICE)	514	57.13
PMS4 (Ammonia ICE-Battery Hybrid)	485	59.57
PMS5 (Methanol ICE)	954	20.44
PMS6 (Methanol ICE-Battery Hybrid)	900	24.97

Conditions considered,

$$(If\ Emission = 0\ then\ Score = 100@If\ Emission = 1200\ \ then\ Score = 0) \quad [34]$$

The PMS1 had a high CO2 eq emission value of 1004,87 tonnes CO2 eq, indicating a substantial contribution to greenhouse gas emissions. At 485.16 tonnes CO2 equivalent, the PMS4 had the lowest emission value, highlighting the potential environmental benefits of using ammonia, a carbon-free propellant, and a battery hybrid system. Other systems, PMS2, PMS3, PMS5, and PMS6, demonstrated lower emissions, demonstrating the potential of alternative fuels and hybrid technologies to reduce the environmental impact of ocean-going vessels.

OPEX

OPEX represents the continual expenses associated with the PMS's operation and maintenance. The cost of fuel has the greatest impact on the OPEX. The following table shows the OPEX for each PMS:

Table 21: OPEX results

Alternatives	USD	Score
PMS1 (Conventional Diesel Engine)	$ 290321	51.61
PMS2 (Diesel Engine-Battery Hybrid)	$ 271315	54.78
PMS3 (Ammonia ICE)	$ 453577	24.40
PMS4 (Ammonia ICE-Battery Hybrid)	$ 424629	29.23
PMS5 (Methanol ICE)	$ 271860	54.69

PMS6 (Methanol ICE-Battery Hybrid)	$ 255290	57.45

Conditions considered,

$$(If\ OPEX = 0\ \ then\ Score = 100@If\ OPEX = 600000\ \ then\ Score = 0) \quad [35]$$

The cost of fuel has a significant impact on the OPEX values. Alternative fuels such as ammonia and methanol are not widely available and are more expensive than conventional fuels such as LSMGO. The highest OPEX for PMS3 is 453,577.36, indicating that ammonia-fueled systems incur greater operating expenses. PMS4 has 424,629.80, indicating that battery systems incur additional costs. At 255,290.48 USD, PMS6 has the lowest OPEX, demonstrating economic efficacy. Other systems have intermediate OPEX values, emphasising trade-offs between ongoing operational expenses and fuel expenses. The following figure shows the graphical representation of the OPEX.

Availability/Bunkering

The data on bunkering availability illustrates the availability of various fuel types at thirteen global ports. LSMGO is commonly used in the maritime industry, while alternative fuels such as ammonia and methanol are available in eight of thirteen ports. Seven out of thirteen ports offer shoreside battery charging (SBC) facilities, indicating the development of electric power infrastructure in the maritime industry but limited availability relative to traditional fuels. These bunkering availability statistics illustrate the current state of fuel infrastructure in the world's main ports, indicating that alternative fuels and electric power are becoming more prevalent but still lag behind traditional fuels such as LSMGO. This could have a negative effect on the viability and operational flexibility of ships powered by alternative fuels or hybrid systems.

Table 22: Availability/Bunkering evaluation based on operational ports.

	Ports	LSMGO	Ammonia	Methanol	SBC
1	Rotterdam	✓	✓	✓	✓
2	Hamburg	✓	✓	✓	✓
3	London	✓			
4	Antwerp	✓	✓	✓	✓
5	Barcelona	✓			✓
6	Shanghai	✓	✓	✓	✓
7	Singapore	✓	✓	✓	✓
8	Ulsan	✓	✓	✓	
9	Dubai	✓		✓	
10	Mumbai	✓			
11	New York	✓	✓	✓	
12	Los Angeles	✓	✓		✓
13	Panama	✓			
	Total	13	8	8	7

Table 23: Availability/Bunkering results.

Alternatives	Bunkering	Availability	Score
PMS1 (Conventional Diesel Engine)	LSMGO	13.00	90.91

PMS2 (Diesel Engine-Battery Hybrid)	LSMGO + SBC	13.70	95.80
PMS3 (Ammonia ICE)	Ammonia (70%)+LSMGO (30%)	9.50	66.43
PMS4 (Ammonia ICE-Battery Hybrid)	Ammonia (70%) +LSMGO (30%) + SBC	10.20	71.33
PMS5 (Methanol ICE)	Methanol (95%) +LSMGO (5%)	8.25	57.69
PMS6 (Methanol ICE-Battery Hybrid)	Methanol (95%) +LSMGO (5%) + SBC	8.95	62.59

Conditions considered,

SBC is given a 10% extra weightage in hybrid PMS.

$$(If\ Availability = 14.3\ \ then\ Score = 100@If\ Availability = 0\ \ then\ Score = 0) \quad [36]$$

Weight

The PMS1, PMS3, and PMS5 all utilise three engines with total weights of 114.9 tonnes, 118.8 tonnes, and 118.8 tonnes. The remaining three systems PMS2, PMS4, and PMS) are hybrid systems that include a battery weighing 126.9 tonnes. The total weight of these systems was determined by adding the weight of the two engines (79.2 tonnes) to the weight of the battery, resulting in a total weight of 206.1 tonnes for each system. The PMS's weight is a crucial factor in the decision-making process, as it impacts the performance of the vessel, its fuel efficiency, and the space required for the PMS.

Table 24: Weight assessment results.

Alternatives	Tonnes	Score
PMS1 (Conventional Diesel Engine)	115	77.35
PMS2 (Diesel Engine-Battery Hybrid)	206	23.42
PMS3 (Ammonia ICE)	119	75.04
PMS4 (Ammonia ICE-Battery Hybrid)	206	23.42
PMS5 (Methanol ICE)	119	75.04
PMS6 (Methanol ICE-Battery Hybrid)	206	23.42

Conditions considered,

$$(If\ Weight = 77\ \ then\ Score = 100@If\ Weight = 246\ \ then\ Score = 0) \quad [37]$$

Based on these calculations, each PMS can be evaluated and compared to determine the most suitable system considering the specific needs and constraints of the vessel.

MARCOS Analysis

After closely evaluating each PMS across the selected criteria using specialised calculations, the following ranking was determined by using MARCOS method. The MARCOS method is used for ranking alternatives based on multiple criteria while seeking a compromise solution. In order to determine the rank of each PMS, the values derived from the calculations are converted into unitless numbers and expressed as scores ranging from 1 to 100. All MARCOS process will be depicted in Tables 25 to 29.

Table 25: Criteria comparison and weight implementation.

	+	+	+	+	+	+
AHP Weight	0.19	0.09	0.47	0.17	0.05	0.03
Power system	**CAPEX**	**RISK**	**Emission**	**OPEX**	**Availability**	**Weight**
PMS1	82.41	50.59	16.26	51.61	90.91	77.35
PMS2	54.67	36.35	21.37	54.78	95.80	23.42

PMS3	51.59	32.36	57.13	24.40	66.43	75.04
PMS4	34.13	16.92	59.57	29.23	71.33	23.42
PMS5	61.02	34.23	20.44	54.69	57.69	75.04
PMS6	40.41	25.79	24.97	57.45	62.59	23.42
AI	82.41	50.59	59.57	57.45	95.80	77.35
AAI	34.13	16.92	16.26	24.40	57.69	23.42

Table 26: Normalization of criteria and alternatives

Normalized						
Power system	**CAPEX**	**RISK**	**Emission**	**OPEX**	**Availability**	**Weight**
PMS1	1.00	1.00	0.27	0.90	0.95	1.00
PMS2	0.66	0.72	0.36	0.95	1.00	0.30
PMS3	0.63	0.64	0.96	0.42	0.69	0.97
PMS4	0.41	0.33	1.00	0.51	0.74	0.30
PMS5	0.74	0.68	0.34	0.95	0.60	0.97
PMS6	0.49	0.51	0.42	1.00	0.65	0.30
AI	1.00	1.00	1.00	1.00	1.00	1.00
AAI	0.41	0.33	0.27	0.42	0.60	0.30

Table 27: Weighted values of criteria and alternatives

Weighted						
Power system	**CAPEX**	**RISK**	**Emission**	**OPEX**	**Availability**	**Weight**
PMS1	0.19	0.09	0.13	0.15	0.05	0.03
PMS2	0.13	0.07	0.17	0.16	0.05	0.01
PMS3	0.12	0.06	0.45	0.07	0.03	0.03
PMS4	0.08	0.03	0.47	0.09	0.04	0.01
PMS5	0.14	0.06	0.16	0.16	0.03	0.03
PMS6	0.10	0.05	0.20	0.17	0.03	0.01
AI	0.19	0.09	0.47	0.17	0.05	0.03
AAI	0.08	0.03	0.13	0.07	0.03	0.01

Table 28: MARCOS calculation

Power system	**Si**	**Ki+**	**Ki-**
PMS1	0.64	0.64	1.83
PMS2	0.58	0.58	1.67
PMS3	0.76	0.76	2.18
PMS4	0.71	0.71	2.04
PMS5	0.58	0.58	1.67
PMS6	0.55	0.55	1.57
AI	1.00		

AAI	0.35

Table 29: MARCOS ranking

Power system	F(Ki+)	F(Ki-)	F(Ki)	Rank
PMS1	0.74	0.26	0.59	**3**
PMS2	0.74	0.26	0.53	**5**
PMS3	0.74	0.26	0.70	**1**
PMS4	0.74	0.26	0.65	**2**
PMS5	0.74	0.26	0.54	**4**
PMS6	0.74	0.26	0.50	**6**

Table 30: MARCOS analysis result.

Power system	Rank
PMS1: Conventional Fuel ICE	**3**
PMS2: Conventional fuel ICE + Battery	**5**
PMS3: Ammonia ICE	**1**
PMS4: Ammonia ICE + Battery	**2**
PMS5: Methanol ICE	**4**
PMS6: Methanol ICE + Battery	**6**

As a result of the MARCOS method, PMS3 has been chosen as the first-rank PMS alternative for under-studied bulk carrier ship propulsion systems. The main difference between MARCOS results with AHP is the position of PMS3 and PMS4 in rank first and second, which are substituting each other. The reason for PMS3's advantage against PMS4 is two main parameters Risk and Weight.

CONCLUSIONS

This study delivered a thorough look at how well different power management systems (PMS) for vessels work, how much they cost, and what risks they pose. Using MARCOS method on dedicated calculations and the Analytic Hierarchy Process (AHP), important criteria of decision-making process have been evaluated. The dedicated calculations conducted involved comprehensive evaluations of various systems, considering the present circumstances, available data, and associated costs. The anticipated future developments, which were accomplished through the application of the Analytic Hierarchy Process (AHP), facilitated the comparison of each criterion and alternative from the perspective of a marine expert, aligning them with desired future outcomes. Based on the current circumstances that were taken into the calculations, the ammonia ICE (PMS3) emerged as the top option due to its lower pollution, acceptable operational costs, and reduced risk, closely followed by the ammonia ICE-battery hybrid (PMS4). However, when future scenarios are considered and criteria are prioritised using the AHP method, the rankings change, and the ammonia ICE-battery hybrid (PMS4) becomes the leading contender. This demonstrates the significant potential of ammonia as an alternative fuel and hybrid system to address the crucial challenge of reducing emissions when given priority. In the AHP classification, the standalone ammonia ICE system (PMS3) holds a firm second place, further demonstrating the potential of ammonia-fueled systems. In third place, the methanol ICE-battery hybrid (PMS6) is also a compelling future option, demonstrating the potential versatility of methanol fuel and hybrid systems.

The PMS5 and PMS6 systems that use methanol stand out as good choices to think about now and in the future. Their high carbon emissions, on the other hand, are a big problem. Innovations like onboard carbon capture units to reduce TTW emissions and the use of "green methanol" could reduce this pollution, making methanol-fueled systems more practical. In the same way, a machine that runs on ammonia could have a lot less pollution over its whole time if it used green ammonia in well to tank emissions. This study points out that infrastructure for alternative fuels and shoreside battery charging (SBC) at ports is one of the most important things to think about. As the company advances towards more environmentally friendly methods, there should be more of this kind of equipment. As technology improves, the costs of alternative fuels and the costs of buying the appropriate engine and safety systems are likely to go down in the future. This makes the case for using hybrid systems and alternative fuels even stronger, which could make them the best choice for future marine activities. Here are some conclusions about why dedicated calculations using the MARCOS method and AHP methods may have produced different rankings, as well as the strengths and weaknesses of each method.

DATA ACCESS STATEMENT

Research data must be shared via data repositories. The publisher, TU Delft OPEN Publishing, requires authors to cite any publicly accessible research data in their reference list and will verify this as a condition of publication. The publisher, TU Delft OPEN Publishing, encourages research data to be made accessible under open licenses that permit reuse freely. References to datasets (data citations) must include a persistent identifier (such as a DOI). The publisher, TU Delft OPEN Publishing, does not enforce particular licenses for research data, where research data are deposited in third party repositories.

CONTRIBUTION STATEMENT

Author 1: Conceptualization; data curation; methodology; validation; writing – original draft. **Author 2:** conceptualization; supervision; writing – review and editing. **Author 3**: conceptualization, data curation, formal analysis, investigation, writing – original draft.

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