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Hybrid marine power systems: techno-economic and environmental optimisation of alternative fuel pathways

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ABSTRACT

This paper offers a comprehensive optimisation tool for the design and assessment of hybrid maritime power systems that combine internal combustion engines, fuel cells, and battery energy storage systems. Using a surrogate-assisted NSGA-II algorithm, the framework concurrently reduces operational expenditure, CO_2 emissions, and life cycle cost assessment. Under constant technical criteria, including system weight and volume, with and without waste heat recovery, four fuel pathways—diesel, LNG, methanol, and ammonia—are evaluated. The results reveal considerable economic and environmental differences compared to the diesel baseline: LNG increases LCCA by 0.5 % (€1.2M) and global warming potential (GWP) by 2 % (1752 kg), while acidification potential (AP) and aerosol formation potential (AFP) decrease by 91 % (914 kg and 1118 kg, respectively). Methanol reduces LCCA by 14.3 % (€35.3M), GWP by 36 % (35,540 kg), and AP/AFP by 81 %, offering a cost-effective and environmentally balanced solution. Ammonia eliminates GWP, AP, and AFP, though with a 10.7 % (€60M) increase in LCCA, demonstrating its potential for long-term decarbonisation. The findings show clear Pareto fronts for every fuel, suggesting that the possible design area is significantly influenced by fuel type. The framework offers practical guidance for designing energy-efficient, low-emission vessels, aiding in sustainable marine energy transitions.

1. Introduction

Marine transportation is responsible for between 2.5 and 3 % of all anthropogenic CO_2 emissions worldwide [1], making it a major contributor to greenhouse gas emissions [2]. The decarbonisation of marine propulsion is a crucial aspect of the global transition towards sustainable transportation systems. Maritime stakeholders are being forced to re-evaluate traditional propulsion systems in favour of cleaner [3], more efficient alternatives because of increasingly strict international laws and rising fuel prices [4, 5]. Hybrid power systems, which consist of internal combustion engines (ICEs), fuel cells (FCs), and battery energy storage systems (BESS), have great potential to reduce emissions and offer flexible operations [6]. The benefits of hybrid propulsion systems [7, 8]—which combine ICEs, FCs, and BESS—in terms of increased

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energy efficiency, reduced emissions, and operational flexibility are becoming more widely acknowledged [9]. Hybrid system design entails intricate trade-offs, including initial capital investment, operational expenses, fuel selection, and emissions profiles [8, 10]. Overlapping technological, economic, and operational uncertainties hinder the achievement of marine decarbonisation [11]. A developing fuel landscape, where alternatives such as LNG, methanol, and ammonia differ significantly in their carbon neutrality, pollutant emissions, and economic feasibility [12, 13], further adds to this complexity [14]. This study contributes to global decarbonisation initiatives, including the United Nations Sustainable Development Goals (SDG 7: Affordable and Clean Energy and SDG 13: Climate Action), and supports pathways toward net-zero emissions in the maritime sector. Previous research has identified key obstacles and energy-related strategies for port-to-ship CO_2 reduction [15, 16]. In addition, recent studies highlight the role of explainable machine learning in predicting fuel consumption in ship engines [17] and the potential of hydrogen-based solutions for achieving net-zero goals in shipping [18].

Multi-objective optimisation methods have been widely used in maritime applications, such as ship routing, hull design, and propulsion system size [19–22]. For example, studies [23–25] have used evolutionary algorithms like NSGA-II to optimise battery sizing and fuel efficiency in hybrid systems. These studies, however, rarely fully account for environmental externalities like NO_x, SO_x, and particulate matter and frequently narrowly concentrate on one-dimensional trade-offs, such as cost vs fuel use.

Existing literature notably lacks the integration of surrogate modelling techniques, such as Random Forests, aimed at enhancing computational efficiency, conducting comprehensive life-cycle environmental assessments (including Global Warming Potential (GWP), Acidification Potential (AP), and Aerosol Formation Potential (AFP)), and incorporating realistic constraints that reflect actual vessel operations (such as weight, volume, and fuel-specific engine parameters). Furthermore, integration into optimisation frameworks is still largely unexplored in the literature, despite Waste Heat Recovery (WHR) systems' acknowledged potential to improve energy efficiency and lessen environmental impacts [9]. In the evaluated configurations, the WHR system utilises exhaust gas temperatures typically ranging from 250 °C to 450 °C, depending on engine load and fuel type. These temperature levels are suitable for conversion via Organic Rankine Cycle (ORC) systems, which have been shown to significantly enhance overall vessel energy efficiency [26].

This research employs the non-dominated sorting genetic algorithm II (NSGA-II) as the primary multi-objective optimisation technique, owing to its robustness, established convergence characteristics, and extensive utilisation in marine energy system design. NSGA-II has undergone significant validation in recent high-impact studies concerning hybrid propulsion sizing and control, and it is endorsed in the newest reviews of maritime optimisation methodologies [10, 27, 28]. The application of NSGA-II alongside surrogate modelling exemplifies contemporary best practices in optimising ship energy systems, particularly for multi-objective, constraint-laden challenges where Pareto-optimum trade-offs are essential.

The approach creates Pareto-optimal solutions for a medium-sized cruise ship by combining emission modelling, lifecycle cost assessment (LCCA), and vessel-specific physical restrictions. The study evaluates key marine fuels—diesel, LNG, methanol, and ammonia—under uniform design parameters, offering practical insights into optimal configurations that balance cost-effectiveness and environmental regulations. The results provide evidence-based recommendations for marine engineers, system integrators, and policymakers in planning the future of low-carbon maritime operations.

Contribution and novelty of this study

By putting forth a solid, data-driven optimisation framework for the design of hybrid marine energy systems, the current study builds on earlier research and includes the following innovative contributions:

- The combination of a surrogate-assisted NSGA-II algorithm with random forest modelling presents a novel strategy, effectively minimising computational complexity while tackling multiple objectives, such as LCCA, CO_2 emissions, and OPEX. This approach is relatively rare in studies focused on maritime propulsion.

- The in-depth comparison of four fuels (diesel, LNG, methanol, and ammonia) using a single framework that takes into account both economic and environmental factors (GWP, AP, and AFP) adds depth to the research and fills a vacuum in the literature.
- The study also incorporates practical vessel-specific physical constraints, such as weight and volume limitations.
- The incorporation of waste heat recovery (WHR) scenarios and their effects on system efficiency represents a practical and innovative approach, given that WHR is frequently under-examined in hybrid system analyses.
- The emphasis on a multi-objective optimisation framework that integrates technical, economic, and environmental trade-offs offers a comprehensive tool for decision-makers, representing an advancement over studies that concentrate on singular objectives, such as cost or fuel consumption.

Unlike previous studies, this one provides a useful optimisation toolkit to give system integrators, shipyards, and policymakers clear, evidence-based pathways toward economically and environmentally optimal marine propulsion solutions, rather than just comparing technological alternatives.

2. Case study details

The medium-sized cruise ship M/S Birka was chosen as a representative case study to assess the proposed hybrid propulsion system. M/S Birka conducts daily voyages in the Baltic Sea, connecting Stockholm and Mariehamn, with a capacity to host up to 1,800 passengers [29]. The consistent route of this vessel, along with its energy-intensive operations and varied power requirements, positions it as an excellent subject for evaluating the effectiveness of the hybrid system.

The M/S Birka was selected as a case study because of its clear operating schedule, the potential for hybridisation, and propulsion features that are representative of larger short-sea and medium-range vessel classes. The operational profile—characterised by cyclical power requirements, frequent port visits, and significant hotel loads—resembles that of RoPax ferries, coastal vessels, and offshore service ships. The analysis is specific to this vessel; however, the optimisation methodology, including modular sizing and control architecture, can be adapted for different ship types by adjusting operational inputs and design limitations. The study offers a transportable framework for evaluating the viability of hybrid propulsion in various maritime applications.

2.1 Technical Specifications

M/S Birka possesses two propulsion systems, each consisting of a primary engine, gearbox, and propeller. The principal technical specifications are presented in Table 1. To meet the thermal energy requirements for passenger accommodations and ship operations, the ship's current energy system includes technologies for recovering waste heat [29, 30].

Table 1 Parameters of the case study ship

Parameter	Value
Length	176.9 m
Breadth	28.6 m
Passenger Capacity	1800
Main Engines	Wärtsilä 6L46
Rated Power (Main Engines)	4X 5,850 kW each
Auxiliary Engines	Wartsila 6L32
Rated Power (Auxiliary Engines)	4X 2760 kW each
Boilers	2X 4500 kW each

2.2 Operational Profile

The ship's daily activities consist of several stages with differing energy requirements, as depicted below:

1. Departure from Stockholm (evening): Moderate propulsion power as the vessel departs the harbour and navigates towards the open sea.

2. Drifting on open water (overnight): Insignificant propulsion demands, with auxiliary systems ensuring passenger comfort and operational preparedness.

3. Arrival in Mariehamn (morning): Low-speed manoeuvres during docking operations necessitate precision and emissions-free performance.

4. Daytime return voyage to Stockholm: sustained propulsion power for cruising, along with considerable auxiliary and thermal energy requirements for passenger amenities.

The standard operational profile encompasses significant fluctuations in power demands for propulsion, auxiliary systems, and thermal energy as presented [29]. The original authors performed a thorough examination of the energy and exergy efficiency of the ship's power plant [30]. Additionally, they investigated optimisation possibilities via load allocation schemes and system-level improvements encompassing dynamic exchanges between electrical and mechanical energy [31]. This study proposes a fuel-efficient and load-profile-refined operational strategy. The two operational voyages are hypothetical operating profiles based on the vessel's operational schedule and power demand trends. Two altered operational scenarios are presented:

1) A delayed departure strategy and

2) A slower cruising speed approach (slow steaming).

Delaying departure reduces sailing time, increases engine efficiency, and permits systems to recover waste heat to fulfil thermal demand, removing the need for auxiliary boilers. Instead of low-efficiency drifting, slower cruising uses slow steaming to recover waste heat and allow mechanical engines (MEs) to cover the electric load throughout transit. The two refined operational profiles derived from these techniques are presented in Figure 1. Figure 1(a) presents the mechanical power profile of the original M/S Birka voyage, derived from the data in Table 3 [29]. Figures 1(b) and 1(c) display the suggested operating methods—Slow Steaming and Delayed Strategy—that the authors put forward to evaluate the technical, economic, and environmental impacts of changes in operation management.

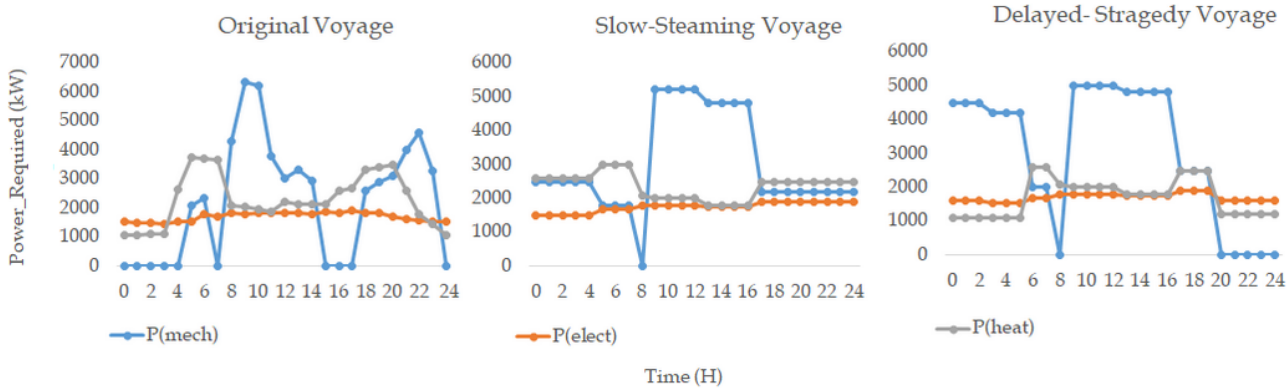

Fig. 1 Operational load profile studied

2.3 Proposed hybrid propulsion system and component sizing

The system architecture uses dual-fuel engines that run on alternative fuels (methanol, ammonia, and LNG) as the main source of propulsion, with hydrogen FCs and a BESS serving as backups, as presented in Figure 2. The hybrid architecture offers the ability to function in various modes, guaranteeing optimal performance in different operational conditions [7]. The proposed architecture is based on hybrid system layouts that have been validated in existing literature. Zheng et al. [10] utilised a diesel-based internal combustion engine-battery configuration as advised by seasoned shipbuilders. This study enhances this concept by incorporating alternative low-carbon fuels, hydrogen FCs, and multi-objective optimisation of environmental and economic factors, specifically designed to address realistic vessel constraints. This offers a prospective framework appropriate for assessing next-generation marine power systems.

The integration of energy sources into the propulsion system occurs in the following manner:

1. Dual-Fuel Engines [32]:
   i. These engines provide the main source of propulsion power in high-demand situations, like cruising.
   ii. Alternative fuels are kept in special tanks, and the engines are tuned for maximum efficiency and low emissions of NO_x and particulate matter.
2. Hydrogen FCs [33]:
   i. Hydrogen FCs provide power with no emissions, making them suitable for consistent operations, like low-speed cruising or remaining at port.
   ii. Liquid hydrogen is stored in cryogenic tanks, which guarantee optimal energy density and effective space utilisation.
3. BESS [34]:
   i. Lithium-ion batteries deliver clean energy during periods of high demand and low-power activities, like navigating a harbour.
   ii. The batteries are also capable of recovering excess energy from the engines when they are operating at low loads or during deceleration.

2.3.1 Operational modes

The hybrid propulsion system accommodates many operational modes to align with the ship's fluctuating power requirements:

- Engine Mode [32]: In high-power cruising situations, the dual-fuel engines serve as the principal energy source, while the batteries and FCs provide supplementary support for transient peaks.
- Hybrid Mode [21, 35, 36]: The engines, FCs, and batteries collaborate to enhance efficiency during mid-range operations, balancing power output while reducing fuel consumption.
- Zero-Emission Mode [37–39]: During port operations, the onshore electricity delivers clean, silent energy, thereby eradicating local emissions and diminishing noise and vibrations.

Although the analysis presupposes the feasibility of full WHR integration and access to IEC-compliant shore power infrastructure, these are idealised assumptions that are consistent with standard practice in future-focused marine decarbonisation studies. Fallback options, such as partial WHR deployment or onboard auxiliary generation, may be considered in locations that are less equipped.

2.3.2 Energy flow and system components

The system consists of bi-directional DC/DC converters for regulating the power flow from the battery and FC, complemented by an energy management system (EMS) to enhance power distribution. This EMS guarantees that components operate within defined limits, maintaining efficiency and minimising emissions. The proposed architecture balances the benefits of fuel's clean combustion, hydrogen's zero-emission potential, and the high energy efficiency of batteries. This design facilitates operational flexibility and sustainability objectives for medium-sized cruise ships while complying with the essential space and weight limitations pertinent to passenger vessels.

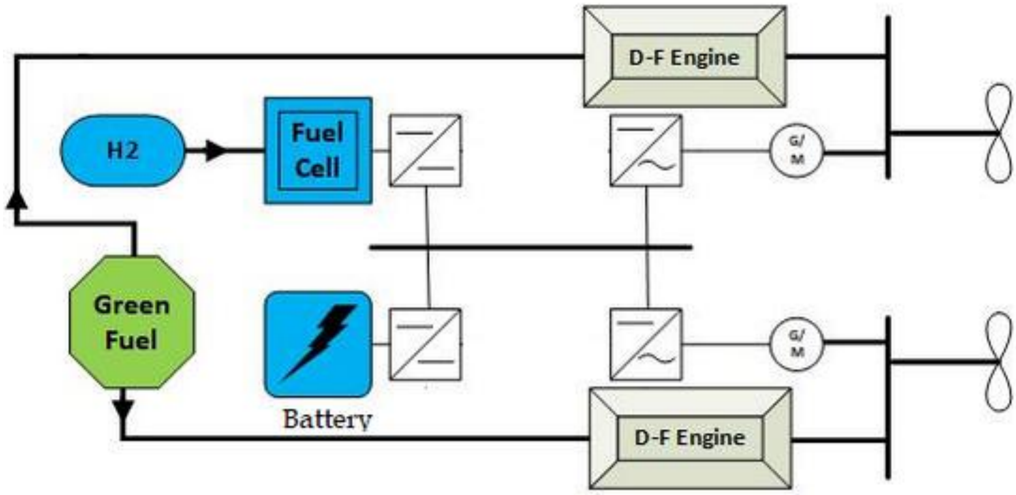

Fig. 2 Proposed hybrid power system

To guarantee that the optimisation results are practically feasible, the sizing of components, including fuel storage systems, FCs, and batteries, was restricted by the anticipated weight and volume allowances aboard M/S Birka. These limitations reflect the practical integration constraints that exist within the vessel's current operational routines and technical spaces.

3. Methodology

This part offers a thorough modelling and optimisation tool meant to evaluate hybrid maritime power systems combining ICEs, FCs, and BESS. Beginning with the examination of operational load profiles, the approach is a multi-step process that progresses through system pre-sizing depending on propulsion strategies and finishes with a surrogate-assisted multi-objective optimisation. Adhering to limits on total system weight and volume, the main goals are to reduce operating expenditure (OPEX), CO_2 emissions, and life cycle cost assessment (LCCA). Environmental effect indicator quantification comprises measures including Global Warming Potential (GWP), Acidification Potential (AP), and Aerosol Formation Potential (AFP). The framework enables a comparison across several fuels, including diesel, LNG, methanol, and ammonia.

3.1 Analysis of Operational Load Profiles and Preliminary Sizing of Hybrid Propulsion Systems

Two updated operating scenarios—delayed departure and slower cruising—are introduced before. Shore power supplies the vessel's electrical load and recharges onboard battery systems during port stays, enabling zero-emission operations. Subsequently, the optimisation focuses on determining the optimal hybrid power system for the vessel's sailing phase. This system should provide a balanced solution that is not only economically viable but also environmentally friendly and spatially efficient.

3.1 Optimisation procedure, design variables, and objectives

The suggested hybrid power system has three main parts: a lithium-ion BESS for balancing energy use and operating without emissions, a Proton Exchange Membrane (PEM) FC unit that provides clean power [40], and an Internal Combustion Engine (ICE) that can run on different types of fuels. Three continuous design factors are examined in the optimisation: the ICE power rating, the FC power rating, and battery capacity. Every design candidate is represented as a vector of real values:

$$x = [\text{Battery, FC, and Engine}] \tag{1}$$

Multi-objective optimisation formulation is represented as:

$$\min_{\vec{x}} \vec{f}(\vec{x}) = [f_1(\vec{x}), f_2(\vec{x}), f_3(\vec{x})] = [\mathrm{LCCA}, \mathrm{CO_2}, \mathrm{OPEX}] \tag{2}$$

Subjected to:

$$g_1(\vec{x}) = W_{\text{total}}(\vec{x}) - W_{max} \leq 0$$
$$g_2(\vec{x}) = V_{\text{total}}(\vec{x}) - V_{max} \leq 0 \quad (3)$$

Design Variables are represented as:

$$\vec{x} = [E_{\text{BAT}}, P_{\text{FC}}, P_{\text{ICE}}] \in \mathbb{R}_+^3 \quad (4)$$

The design space was established according to practical sizing limitations for M/S Birka-class vessels. The optimisation variables and their constraints were as follows:

- Battery capacity: 9,000–12,000 kWh.
- ICE power rating: 9,000–12,000 kW.
- FC power rating: 1,500–2,000 kW.

The ranges indicate constraints related to physical integration (weight and volume), propulsion needs, and the maturity of technology. The upper limit for the FC is selected to ensure high efficiency under steady-state operation, enable modular redundancy, and support extended zero-emission sailing or auxiliary load coverage. The battery size provides adequate energy for hybrid support, whereas the power range of the internal combustion engine matches the vessel's peak propulsion requirements during cruising.

The following goals are simultaneously minimised:

1. Life Cycle Cost Assessment (LCCA, €) — Comprises CAPEX, OPEX, fuel expenses, maintenance costs, port energy, component replacement costs, and carbon taxation [12, 41]. It is expressed as follows:

$$\text{LCCA} = \text{CAPEX} + \sum_{t=1}^{T} \frac{\text{OPEX}(t) + \text{CarbonTax}(t)}{(1+r)^t} \quad (5)$$

where:

- T = Lifetime period (years),
- r = discount rate,
- CAPEX = Capital / investment cost,
- OPEX(t) = fuel, electricity, replacement costs, and maintenance costs at year t,
- CarbonTax(t) = annual CO_2-related tax.

The life cycle cost assessment (LCCA) and operational expenditure (OPEX) models incorporate detailed cost components to ensure economic accuracy. Based on power- and energy-based unit rates, capital costs encompass the installation of internal combustion engines, battery systems, and FCs. The operational expenses include the consumption of fuel and electricity, the maintenance of ICEs and FCs, and battery degradation based on a fixed cycle life. Additionally, CO_2 emissions are subject to a carbon levy throughout the vessel's operational lifespan. Table 2 provides a comprehensive summary of the unit cost parameters.

2. For any emission x, the tailpipe emissions [12] are computed as:

$$E_x = EF_x \cdot FC \forall x \in \{CO_2, CH_4, N_2O, NO_x, SO_x, PM_{10}\} \quad (6)$$

where:

- E_x = emissions of pollutant x (kg),
- EF_x = emission factor for pollutant x (kg/kg fuel),
- FC = fuel consumption (kg).

Emission factors are used to calculate environmental performance indicators [42–45].

Table 2 Key economic input factors used in the LCCA and OPEX modelling framework

Component	Unit	Cost	References
ICE CAPEX	€/kW	180- 1330	[46]
Battery CAPEX	€/kWh	210	[47]
FC CAPEX	€/kW	1500 × 1.2	[47]
Battery Lifetime	cycles	5000	[47]
F.C Lifetime	hours	20,000	[47]
Battery Replacement Cost	€/cycle	75 %* CAPEX	[12]
ICE Maintenance	€/kWh	0.014–0.017	[12]
FC Maintenance	€/kW	10 % CAPEX	[12]
Port Electricity Cost	€/kWh	0.081	[48]
Fuel Prices	€/kg	0.34–1.14	[48]
Carbon Tax	€/ton CO_2	85	[48]

The metrics assessed include Global Warming Potential (GWP), Acidification Potential (AP), and Aerosol Formation Potential (AFP), which come from the specific emissions of pollutants like particulate matter, CO_2, CH_4, N_2O, SO_x, and NO_x for each type of fuel. Emissions for each fuel type are calculated based on fuel consumption, yielding detailed environmental profiles.

3. The Global Warming Potential (GWP) quantifies the comparative climate impact of greenhouse gases using IPCC equivalence factors [49]:

$$\mathrm{GWP} = E_{CO_2} + 36 \cdot E_{CH_4} + 298 \cdot E_{N_2O} \tag{7}$$

where E_{CO_2}, E_{CH_4}, and E_{N_2O} are the emissions (kg) of CO_2, CH_4, and N_2O, respectively, 36 and 298 are the 100-year global warming potential factors for CH_4 and N_2O, per IPCC AR6.

4. The acidification potential accounts for contributions from sulphur and nitrogen oxides [49]:

$$\mathrm{AP} = E_{SO_x} + 0.7 \cdot E_{NO_x} \tag{8}$$

where:

- E_{SO_x} = sulphur oxides (kg),
- E_{NO_x} = nitrogen oxides (kg).

5. AFP shows precursor compounds and secondary particle generation [49]:

$$\mathrm{AFP} = 0.5 \cdot E_{PM_{10}} + 0.54 \cdot E_{SO_x} + 0.88 \cdot E_{NO_x} \tag{9}$$

where:

- $E_{PM_{10}}$ = primary PM10 emissions (kg),
- E_{SO_x}, E_{NO_x} = precursor gases contributing to secondary aerosol formation.

6. The total system weight W_{total} and volume V_{total} are calculated as:

$$W_{\text{total}} = \sum_{i \in \{\text{BAT,FC,ICE}\}} W_i, V_{\text{total}} = \sum_{i \in \{\text{BAT,FC,ICE}\}} V_i$$

$$W_{\text{BAT}} = \alpha_{\text{BAT}} \cdot E_{\text{BAT}}, W_{\text{FC}} = \alpha_{\text{FC}} \cdot P_{\text{FC}}, W_{\text{ICE}} = \alpha_{\text{ICE}}(f) \cdot P_{\text{ICE}} \tag{10}$$

$$V_{\text{BAT}} = \beta_{\text{BAT}} \cdot E_{\text{BAT}}, V_{\text{FC}} = \beta_{\text{FC}} \cdot P_{\text{FC}}, V_{\text{ICE}} = \beta_{\text{ICE}}(f) \cdot P_{\text{ICE}}$$

where:

- α,β = weight, volume coefficients,

- f = fuel type,
- E_{BAT} = battery energy (kWh),
- P_{FC}, P_{ICE} = rated power of FC and ICE (kW).

System weight and volume restrictions are in place to guarantee practical viability on a medium-sized cruise ship [50]; the entire system weight and volume are limited to 4,000 tonnes and 8,000 m^3, respectively [51]. Component-specific estimates are used: batteries (10 kg/kWh and 0.005 m^3/kWh), FCs (5 kg/kW and 0.003 m^3/kW) [47], and internal combustion engines, with specifications varying by fuel type [52].

A Random Forest Regressor (RFR) was trained using samples created with Latin Hypercube Sampling (LHS), serving as a cost-effective substitute model. The surrogate model [53] provides an approximation of the relationship between system configuration variables ([Battery, FC, ICE]) and key performance indicators ([LCCA, CO_2, OPEX]). This approach effectively reduces computational overhead while maintaining accuracy. The optimisation process implements the NSGA-II [54–56] algorithm. The optimisation parameters consist of a population size of 100 individuals, assessed over 100 generations [10]. All candidate solutions are subjected to feasibility assessments and are limited to defined parameters to guarantee practical and executable system configurations.

3.2 Limitations and Assumptions

The approach is robust and based on realistic vessel limits; however, various modelling assumptions and limitations were needed for tractability and clarity. These are listed below.

- Assume cryogenic hydrogen storage and model ammonia as a zero-carbon fuel without considering safety requirements like double-walled tanks, ventilation, and detection. Safety-related space and cost constraints were qualitatively acknowledged but not addressed in the fundamental optimisation model. Future work could incorporate these constraints using safety factor-based layout design or cost penalties.
- The system boundary only includes the ship's power system. Port logistics, hull hydrodynamics, infrastructure, and crew accommodation energy are excluded. This narrow scope is sufficient to evaluate propulsion design performance and feasibility against diesel baselines.
- Dual-fuel engines are assumed to operate mostly in dual-fuel mode with a 5 % pilot fuel (e.g., diesel). Control-level models may handle transient behaviour, mode-switching inefficiencies, and combustion variations.
- Although ammonia-fuelled ICEs are assessed, this technology is evolving. Market deployment, emissions, and cost estimates are estimates and may change. Ammonia situations are illustrative, not final.
- The Random Forest surrogate model was trained on a limited dataset generated through Latin Hypercube Sampling, so its predictive accuracy is confined to the sampled design space. Extrapolation beyond this range or under highly dynamic operating conditions may introduce uncertainty. Furthermore, static assumptions regarding component efficiencies and demand profiles were applied to reduce computational cost, and the chosen optimisation settings (100 individuals, 100 generations) balance accuracy with efficiency but may not fully capture very fine Pareto variations. These factors collectively define the scope within which the optimisation results remain reliable and representative.

4. Results and Discussion

This section provides the results and analysis of the voyage strategy evaluation, the economic comparison of CAPEX and OPEX, FC capacity optimisation, and operating expenditures. The study analyses the relationships between LCCA, OPEX, and emissions; investigates environmental impacts using AP, GWP, and AFP indicators; and concludes with a sensitivity analysis to evaluate the robustness of key parameters.

4.1 Voyage strategy evaluation and selection

This study examined the baseline operational pattern (original journey), a delayed departure strategy, and a reduced-speed or slow-steaming alternative. The most cost-effective operating mode was determined by analysing each profile's fuel costs. Each scenario's fuel mass was determined using the marine diesel oil (MDO)'s lower heating value (LHV) and waste heat recovery (WHR) systems' thermal load satisfaction effects. During port stays, the vessel was believed to link to shore power infrastructure, allowing onshore electricity to cover hoteling demands without onboard supplemental generation. The vessel's MDO-powered ICEs propelled it during the journey, with excess mechanical energy going to auxiliary systems. Waste heat recovery devices in the primary engines provided the most navigational thermal energy. In Figure 3, fuel prices for the three trip techniques are compared to highlight the financial impact of each ship's energy system. The delayed profile saved 8,565 kg of diesel and recovered 13,500 kWh of thermal energy, the most of any scenario. This profile had the lowest net fuel consumption of 18,000 kg and the lowest journey cost of 28,000 USD. While maintaining the propulsion regime, slow steaming yielded the highest thermal recovery (23000 kWh) and the lowest fuel savings (5,154 kg), resulting in the highest fuel consumption (36000 kg) and voyage cost (USD 49,000). The original technique, which included engine stops to align arrival timings with boarding timetables, recovered thermal energy (14,500 kWh) but saved fuel (5,339 kg) like slow steaming. The fuel consumption was 24,000 kg and cost USD 36,000, placing it between Delayed and Slow. After integrating waste heat recovery and restricting shore power usage, the delayed strategy is the most thermally and economically effective. The vessel's original operating voyage plan includes a pause offshore to synchronise arrival with early morning port access. This study presents an alternative delayed departure approach to maintain the targeted arrival time, reduce low-efficiency drifting, and enhance waste heat utilisation.

4.2 Economic analysis (CAPEX vs OPEX)

Figure 4 demonstrates major cost trade-offs between diesel, methanol, LNG, and ammonia. Diesel has the lowest capital outlay (CAPEX), approximately €6–7 million, with a reasonable OPEX of €45,000–€50,000. Methanol has the lowest operational costs (OPEX), €37,500 to €42,500, but higher capital costs (CAPEX), €12 million, than diesel. Although ammonia has the highest recurring expenditures, topping €50,000 in some cases, both LNG and ammonia require considerable initial investment costs, usually €16–20 million.

4.3 FC capacity (kW) and operating expenditure (OPEX, in €)

Figure 5 compares FC capacity (kW) and operating expenditure (OPEX, in €) for ammonia, diesel, LNG, and methanol maritime fuels. As FC size increases across all fuel types, OPEX rises. Methanol consistently has the lowest running costs, at €43,000 as the FC capacity approaches 2 MW, proving its economic advantage throughout power capacities. Diesel and LNG have similar intermediate operational expenses, €42,500 to €48,000, while diesel has somewhat higher OPEX at FC capabilities. Ammonia again has the greatest operational expenses, increasing from €47,500 to over €52,500 as FC capacity grows from 1500 to 2000 kW.

This analysis shows that methanol is the best fuel for operational use, especially in high-capacity scenarios, while ammonia is economically challenging and requires considerable operational justifications or environmental regulatory incentives.

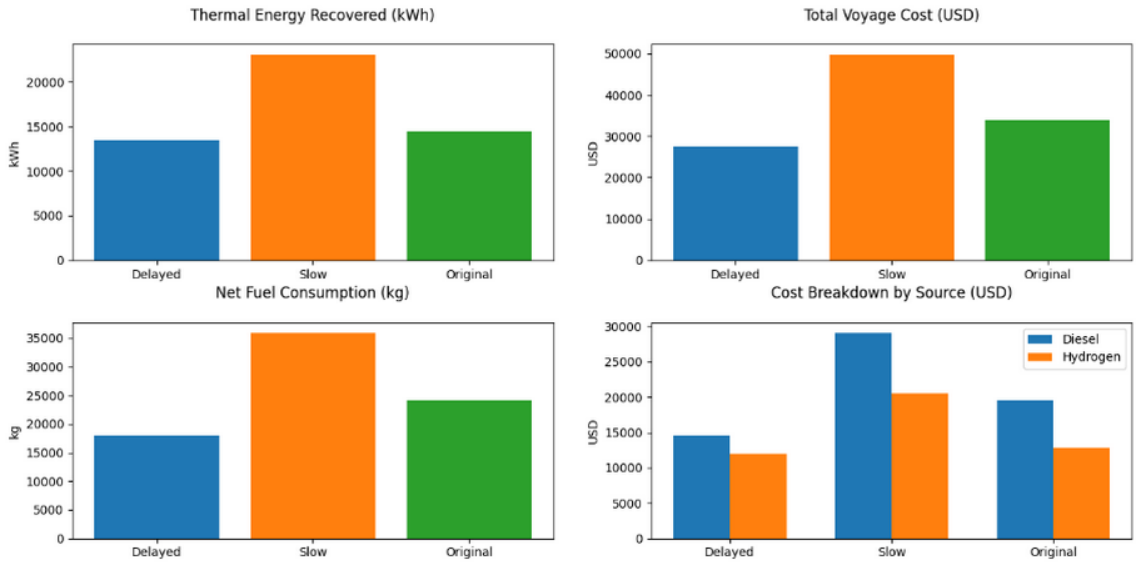

Fig. 3 Comparative analysis of thermal energy recovery, fuel consumption, and economic indicators across three voyage operational scenarios (“Delayed”, “Slow”, and "Original")

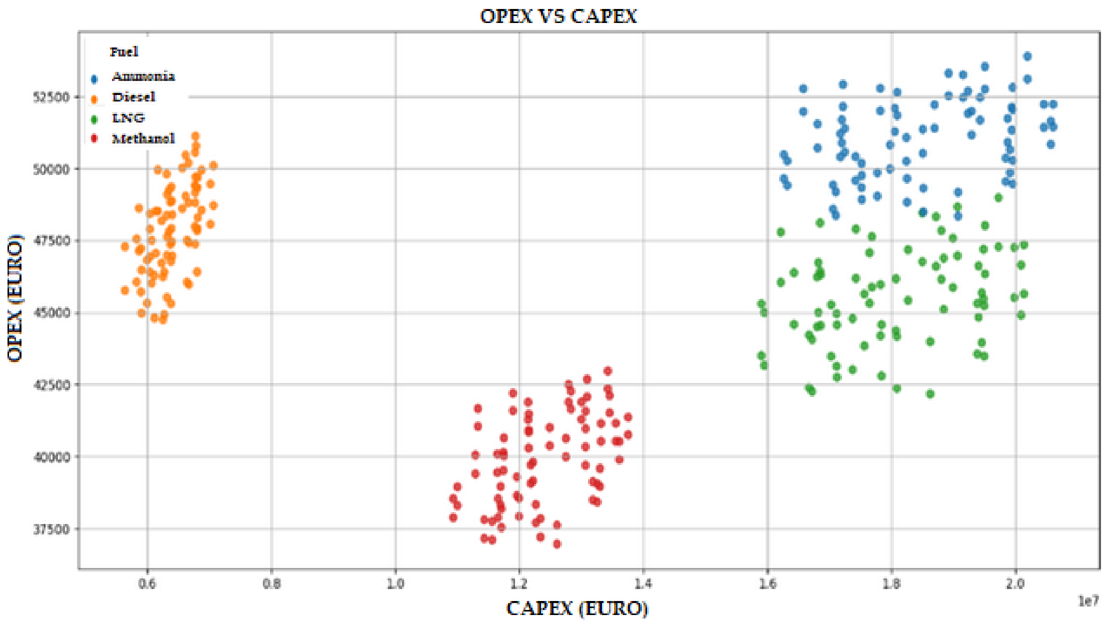

Fig. 4 Operational Expenditure (OPEX) vs Capital Expenditure (CAPEX) for ammonia, diesel, LNG, and methanol fuels

4.4 LCCA vs OPEX vs Emission

A 3D scatter plot of OPEX, LCCA, and CO_2 emissions was created to evaluate economic and environmental trade-offs across various fuel types and WHR scenarios (Figure 6). Only 30 % of the simulated data points were presented for clarity without affecting results. To standardise fuel comparisons, median values were used.

Methanol with WHR has the lowest LCCA (€202.5 M) and OPEX (€39.6k/year) among carbon-emitting fuels, producing 212 million kg of CO_2 annually. Using LNG with WHR resulted in a 192 million kg reduction in CO_2 emissions, €44.7k OPEX, and €231.9 M LCCA. Diesel is cost-competitive (LCCA €232.9 M, OPEX €47.2k) but emits the most CO_2 (318 million kg), highlighting its environmental disadvantage. In contrast, ammonia has negligible CO_2 emissions and LCCA values of €261.2 M (with WHR) and €265.2 M (without WHR). These values are greater than fossil fuels because of infrastructure and fuel costs, but regulatory incentives may compensate. WHR consistently lowered OPEX and LCCA across fuels. These findings show that WHR improves money-saving and environmental efforts and that methanol and ammonia are good hybrid engine fuels in different policy and cost scenarios.

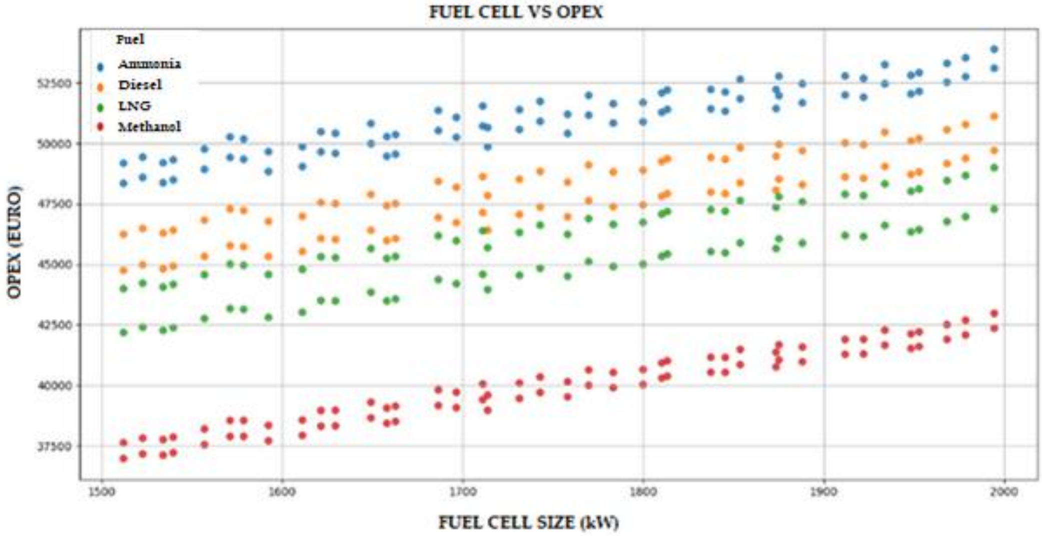

Fig. 5 Operational Expenditure (OPEX) vs FC size for case study ship powered by ammonia, diesel, LNG, and methanol

4.5 AP, GWP, AFP vs LCCA

Table 3 shows considerable economic and environmental differences between alternate marine fuels and diesel, the baseline. LNG has a 0.5 % (€1.2M) increase in life cycle cost assessment (LCCA) and a 2 % (1752 kg) increase in global warming potential. But acidification potential (AP) (914 kg) and aerosol formation potential (AFP) (1118 kg) dropped by 91 %. Using methanol reduces LCCA by 14.3 % (35.33M€), GWP by 36 % (35540 kg), and AP and AFP by 81 %. Ammonia was the most environmentally friendly, eliminating GWP, AP, and AFP 100 % despite a 10.7 % (€60M) increase in LCCA. The data shows that ammonia can decarbonise over time, but methanol offers a better cost-efficiency-environmental balance.

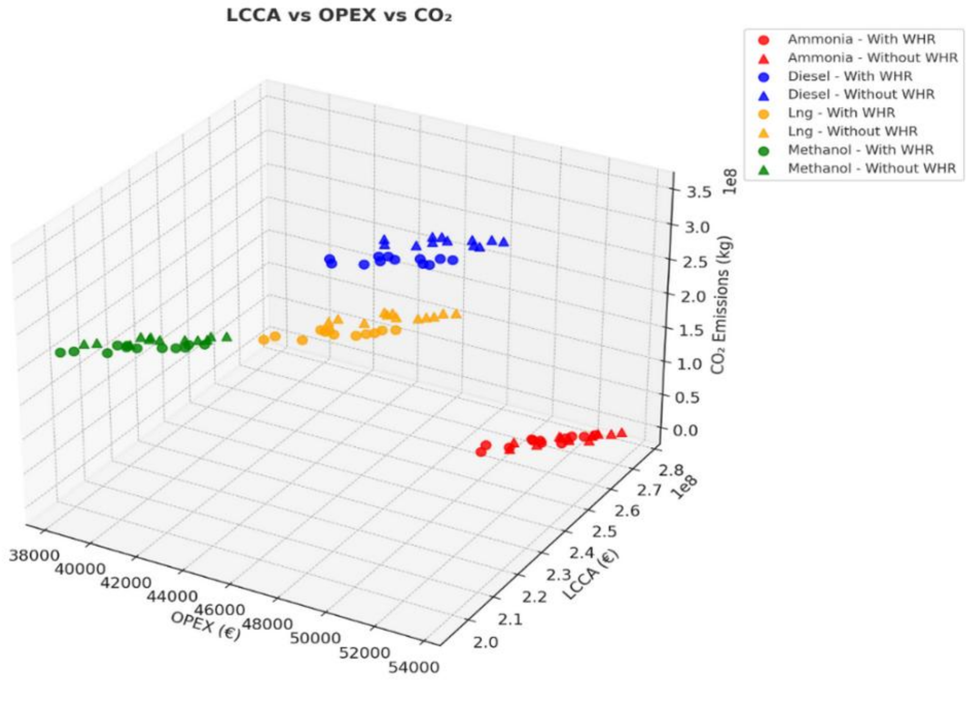

Fig. 6 Three-dimensional comparison of OPEX, LCCA, and CO_2 emissions for the case study ship fuelled by ammonia, diesel, LNG, and methanol

Table 3 The percentage differences in LCCA, GWP, AP, and AFP between alternative fuels and diesel (positive values imply increases, while negative values represent reductions in comparison to diesel)

Fuel	Δ LCCA (%)	Δ GWP (%)	Δ AP (%)	Δ AFP (%)
LNG	0.5	2	-91	-91
Methanol	-14.3	-36	-81	-81
Ammonia	10.7	-100	-100	-100

4.6 Sensitivity Study: adjusting CAPEX and Battery CAPEX

A sensitivity study assessed the resilience of optimal designs to capital investment uncertainty by altering CAPEX by ±20 % at median values based on simulation results. The investigation focused on two extreme scenarios: ammonia at €0.35/kg and methanol at €0.825/kg. These are fuel-specific, optimistic, and pessimistic economic forecasts. LCCA essentially rises linearly with CAPEX for both fuels, showing hybrid system investments' cost-weighted characteristics (Figure 7). Ammonia has a lower life cycle cost analysis (LCCA) at all capital expenditure (CAPEX) levels; therefore, it handles capital cost variations better when fuel prices are favourable. According to this study, methanol is a viable option, but ammonia may be more cost-effective provided its handling infrastructure and safety measures can be managed affordably.

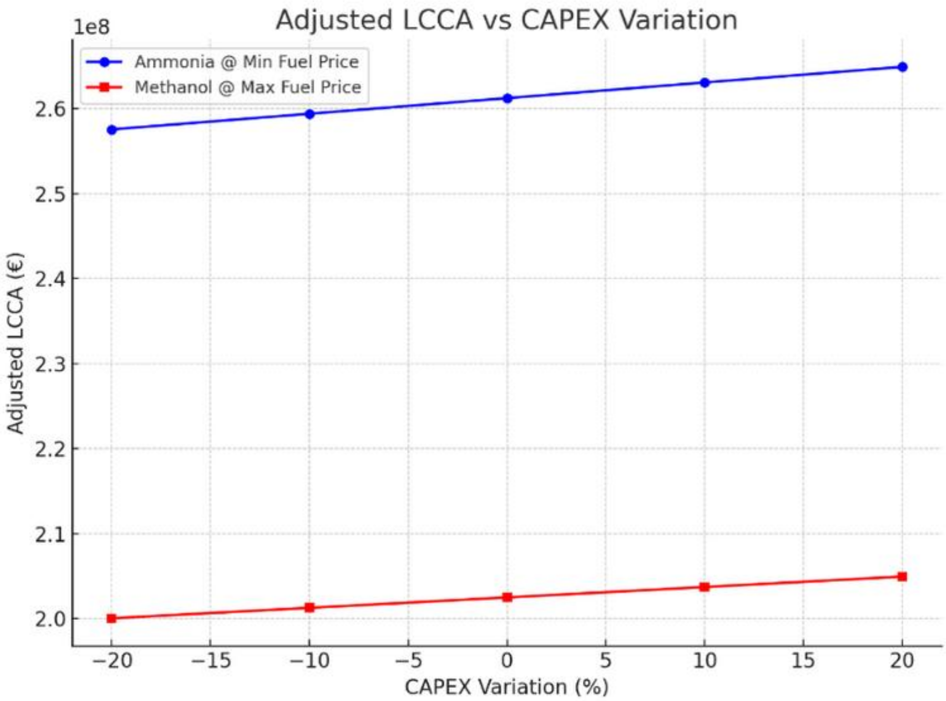

Fig. 7 LCCA as a function of CAPEX variation (±20 %) for ammonia and methanol configurations

Figure 8 demonstrates the sensitivity of the adjusted Life Cycle Cost Assessment (LCCA) to fluctuations in battery cost for various fuel types. In the evaluated range (€150–€270/kWh), the LCCA of all fuels increases modestly, suggesting a relatively low sensitivity to changes in battery cost. Methanol consistently exhibits the lowest LCCA, followed by diesel and LNG, which have virtually identical cost profiles. Although ammonia has the potential to provide environmental benefits, it has the maximum LCCA in the range. The data indicate that the economic hierarchy among the options under consideration is not substantially affected by fluctuations in battery costs, as the relative ranking of fuel types remains unaltered. This underscores the economic resilience of methanol in the face of a variety of battery cost scenarios.

The simulation-based optimisation method and surrogate model trained on M/S Birka's operational profiles ensure that the results appropriately reflect vessel behaviour. The assessment of fuel types uses IMO-compliant emissions parameters, industry-standard pricing criteria, and a standardised techno-economic and environmental framework. The computational approach follows current hybrid marine system research best practices, where real-time experimental validation is often unfeasible due to financial restrictions, complexity, and deployment timeframes. Results provide a solid platform for comparative evaluation and strategic decision-making in early hybrid ship design. Simulation and optimisation are used to build the hybrid propulsion framework, which accounts for real vessel integration restrictions. Retrofitting feasibility is assessed using M/S Birka, a diesel-mechanical cruise ferry.

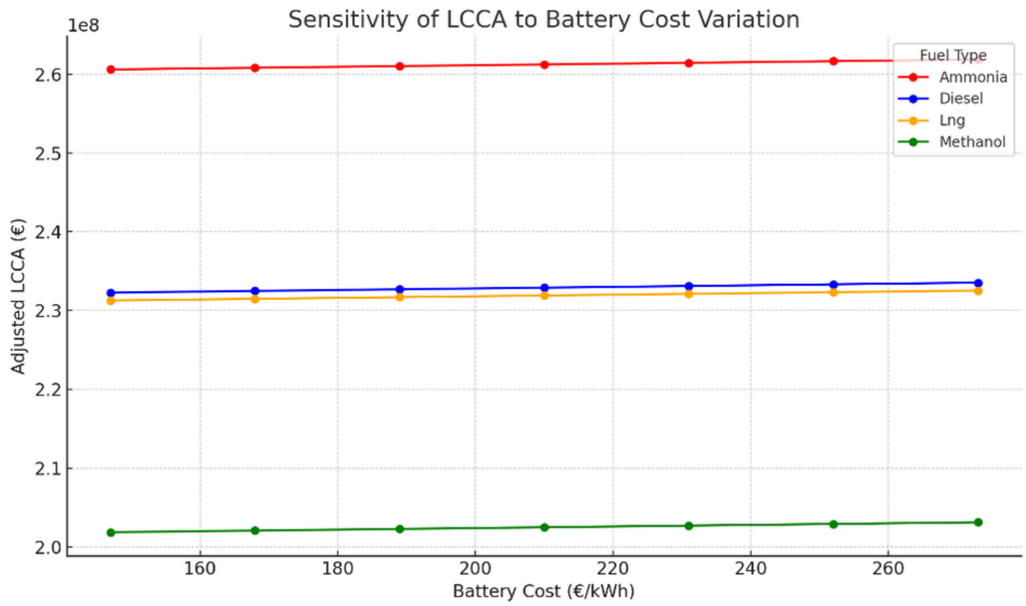

Fig. 8 LCCA variation across fuel types as a function of battery system cost, varied ±30 %

The model considers weight and space constraints, guaranteeing battery and FC capacities (up to 72 tonnes and 60 m³ for batteries) fit without significant ship construction changes. Ammonia and methanol reduce emissions, but they require double-walled tanks, ventilation, and leak monitoring to meet new industry standards [57, 58]. The implementation of shore power, anticipated during port calls, is achievable via IEC-compliant cold ironing systems [59], especially considering the vessel's consistent terminal schedule. Compact exchangers simulate waste heat recovery and can potentially integrate with the vessel's existing thermal systems [60, 61]. These indicators collectively indicate that the optimised hybrid configurations are both theoretically efficient and practically feasible within the technical and operational limitations of the case study vessel.

5. Conclusion

This study established and executed a comprehensive optimisation framework that utilises surrogate assistance to assess hybrid marine propulsion systems by integrating ICEs, FCs, and BESS with various fuel alternatives, including diesel, LNG, methanol, and ammonia. The NSGA-II algorithm was used to concurrently optimise Life Cycle Cost Assessment (LCCA), CO_2 emissions, and Operating Expenditures (OPEX) while adhering to practical constraints regarding system weight and volume. This research yielded several important conclusions:

- The study demonstrates significant techno-economic and environmental differences among the four evaluated fuels. Compared to diesel, LNG shows a 0.5 % (€1.2 M) increase in life cycle cost assessment (LCCA) and a 2 % (1,752 kg) increase in global warming potential (GWP), while acidification potential (AP, 914 kg) and aerosol formation potential (AFP, 1,118 kg) are reduced by 91 %. Methanol reduces LCCA by 14.3 % (€35.33 M), GWP by 36 % (35,540 kg), and AP and AFP by 81 %. Ammonia provides the most environmentally friendly option, eliminating GWP, AP, and AFP, although at a 10.7 % (€60 M) increase in LCCA.
- A significant trade-off between cost and environmental performance was identified, as illustrated by the Pareto front. Low-emission solutions, particularly those utilising ammonia or methanol, present greater economic costs relative to diesel-powered systems. While diesel systems demonstrate

minimal Life Cycle Cost Analysis (LCCA), they yield unacceptable environmental consequences, including CO_2 emissions, Global Warming Potential (GWP), Acidification Potential (AP), and Aerosol Formation Potential (AFP).

- The optimisation findings highlighted that the selection of fuel significantly determines the viable solution space. Distinct, non-overlapping clusters emerged for each fuel type, indicating that changing fuel selection requires a comprehensive recalibration of the optimisation process to determine feasible configurations.
- The inclusion of comprehensive environmental metrics (GWP, AP, and AFP) offered enhanced insights into fuel performance, extending beyond simple CO_2 emissions. Ammonia consistently showed greater environmental advantages across all metrics, while diesel displayed markedly higher air pollution and adverse health effects, underscoring its shortcomings under stringent air quality and health regulations, particularly in proximity to ports.
- According to the analysis, WHR continuously lowers costs and emissions, while ammonia remains the most practical zero-emission solution under favourable policy conditions, and methanol provides the most economical low-emission alternative.
- The sensitivity study demonstrates that ammonia continuously surpasses methanol over the whole spectrum of capital cost fluctuations when priced advantageously, highlighting its robust potential under economically favourable conditions.
- Methanol has emerged as a viable transitional fuel, effectively balancing economic considerations with environmental compliance. Methanol, characterised by moderate costs, low global warming potential, and minimal emissions from acidifying and aerosol-forming pollutants, serves as a viable intermediate solution for achieving full decarbonisation, especially in scenarios where the adoption of ammonia is hindered by infrastructural or technological limitations.
- Ammonia offers significant environmental benefits; however, its implementation necessitates the careful incorporation of safety measures, including double-walled tanks, ventilation, and gas leak monitoring—elements not addressed in this simulation but essential for effective deployment. Methanol, recognised as a potential transitional fuel, relies significantly on the development of emerging bunker infrastructure and the establishment of supportive policy frameworks.

This study highlights significant policy and design implications. Developing truly zero-carbon systems for marine propulsion is feasible from a technological standpoint, yet it presents significant economic challenges. Effective policy mechanisms, including carbon pricing, incentives for green infrastructure development, and targeted subsidies, are essential for facilitating the widespread adoption of cleaner marine fuels. The optimisation framework offers essential assistance to regulators, system integrators, and ship owners by facilitating informed decision-making that aligns with international maritime objectives and local environmental regulations.

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