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Research Article

Hybrid PEMFC–battery systems for marine propulsion: Optimization of efficiency and operational safety

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Abstract. This study presents a critical review and optimization of a hybrid proton exchange membrane fuel cell (PEMFC) battery propulsion system for marine operations under dynamic working conditions. The proposed system incorporates the most current energy management methods such as model predictive control (MPC) and eco-cooling processes to maximize system performance, efficiency, and safety of its work. The system performance is tested during a typical marine load profile and compared to a conventional PEMFC-only baseline configuration that operates without hybrid energy storage or with sophisticated control systems. The findings prove that the hybrid system shows a significant enhancement in operational performance with an increase in efficiency to up to 52.6 % and a significant reduction in hydrogen consumption during the transient load conditions. Moreover, battery support is also integrated to improve load-following capabilities, and minimizing stresses on the fuel cell stack, which is essential for enhanced durability and system reliability. In addition, the given solution enhances thermal control and safety levels because the operating temperatures are kept constant, and fluctuations in the system variables are quickly reduced. The Hybrid design also facilitates a better distribution of the energy and lower auxiliary losses, hence contributing to the greater stability of the system. These results show the potential of hybrid energy storage and enhanced control measures in enhancing the efficiency, sustainability, and safety of marine propulsion systems and can provide a promising avenue to decarbonized maritime energy systems.

Keywords: Hybrid PEMFC–Battery System; Marine Propulsion; Energy Efficiency Optimization; Model Predictive Control (MPC); Operational Safety and Decarbonization

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1. Introduction

Industrial growth, development, and societal progress have always been anchored on energy. The ever-growing global demand, which is a result of an accelerating urbanization, maritime transport, and population increase, has placed unprecedented pressure on conventional fossil fuels (Leng *et al.*, 2022; Markötter *et al.*, 2019; Rao *et al.*, 2024). Although conventional energy systems are stable, they have led to a high level of greenhouse gas emissions, environmental degradation, and an increased rate of climate change. The energy transition has become an urgent need in recent decades, and global bodies like the Paris Agreement provide strong goals of carbon reduction. Here, the maritime industry, which transports nearly 90% of global goods, has become a key facilitator of economic activity as well as a key contributor of emissions (Shahgaldi *et al.*, 2017; V & J.M, 2024; Wang *et al.*, 2025). The combined challenge of maintaining a dependable energy supply with decreasing carbon intensity is thus an issue of global concern and energy optimization and innovation are not merely a technological option but a strategic challenge of sustainable development.

Marine transportation requires energy systems that are not only powerful, but also robust in dynamic operating conditions, due to its scale and complexity (Al-Falahat *et al.*, 2019; Alrwashdeh, 2018a, 2018b). Traditional marine propulsion is highly dependent on heavy fuel oil, marine diesel oil, or liquefied natural gas which, although stable and supported by established infrastructure, poses significant environmental risks. International Maritime Organization (IMO) has increased emission regulations, forcing operators of vessels to use cleaner fuels, optimize the efficiency of engines, and use advanced technologies. Nonetheless, the marine environment is fundamentally different: the propulsion systems are to survive severe weather conditions, fluctuating load conditions, extended travel time, and extreme level of safety needs. Marine energy solutions should thus consider efficiency and reliability in relation to one another whereby marine ships should be able to operate continuously without affecting the safety of the crew or cargo on board. That is why the industry is one of the most challenging experimental environments of implementing the innovative energy systems that could be used to achieve the decarbonization process and address the high standards of the operational quality (Altarawneh *et al.*, 2022; Bayaidah *et al.*, 2023; Göbel *et al.*, 2018).

Renewable energy has emerged as a potential solution to decarbonize marine propulsion. Wind-assist propulsion, solar photovoltaics, and hybrid renewable configurations are some of the technologies that have proven beneficial in reducing fuel consumption as well as emissions. Nonetheless, the intermittent

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and fluctuating characteristics of most renewable sources creates integration challenges in utilizing them in large vessels that require constant and high-power levels (Al-Falahat, Kardjilov, Murtadha, *et al*., 2023; Al-Falahat *et al*., 2022; Qadourah *et al*., 2022). A more viable solution can be found in hybrid renewable arrangements, such as systems in which renewable energy is combined with auxiliary storage facilities or standard engines, by providing an uninterrupted power supply in the quest to harness the opportunities of clean energy. Although wind-assisted systems have the potential to offer partial relief on the use of fuel, and solar has been piloted on ferries and small vessels, upscaling these technologies to larger ocean-going vessels has proved to be challenging. The focus has therefore shifted towards high-end electrochemical devices, especially fuel cells that can directly convert chemical energy into electricity at a high efficiency and zero harmful emissions at the point of use (Lan *et al*., 2022; Nyongesa *et al*., 2024; Qu *et al*., 2024).

Fuel cells have emerged as a promising solution to the development of sustainable marine propulsion because they have the potential to produce clean, efficient, and reliable energy. Among the different types Solid Oxide Fuel Cells (SOFCs), Molten Carbonate Fuel Cells (MCFCs) and Proton Exchange Membrane Fuel Cells (PEMFCs), the latter are best adapted to maritime applications due to a relatively low operating temperature, rapid start-up capability, small size, and power density (Al-Falahat & Alrwashdeh, 2025a, 2025b; Al-Falahat *et al*., 2025; Al-Falahat, Kardjilov, Murtadha, *et al*., 2023; Al-Falahat, Kardjilov, Woracek, *et al*., 2023). Fuel cells can be used as either primary propulsion units or as auxiliary sources of power with the flexibility to serve a wide range of vessel types such as ferries and large cargo ships (Fu *et al*., 2025; Hou *et al*., 2022; Li *et al*., 2025; Ma *et al*., 2025). They can significantly reduce emissions of sulphur oxides (SOx), nitrogen oxides (NOx) and particulate matter, which is in line with the IMO 2020 regulations. In addition, fuel cells enhance onboard safety since they do not involve combustion processes and reduce noise and vibration, which improves the quality of working conditions of crew members. Nonetheless, their widespread adoption can be achieved by dealing with challenges associated with hydrogen storage, price, systemisation, and the prolonged viability under maritime conditions of operation (Harahap *et al*., 2023; Pan *et al*., 2025; Ruiz *et al*., 2015; Wang *et al*., 2011).

PEMFCs have received a lot of attention over the past years as a potential zero-emission propulsion in the maritime sector. They are highly adaptable to the variable power requirements of vessels in manoeuvring operations, cruising, and docking operations due to their capacity to work effectively under constantly changing loads. Their potential has been indicated in several pilot projects and demonstrations. As an example, the paper by Wu *et al.* (2021) provided a comprehensive analysis of the hybrid PEMFC-battery systems and demonstrated that smart load management solutions enhanced the system durability as well as decreased hydrogen usage levels. Equally, European research projects, including FLAGSHIPS, have developed the implementation of large-scale PEMFC systems on passenger ferries and validated their technical viability and environmental benefits *(Gonzalez-Macia et al., 2024; Wang et al*., 2025). The works emphasize the fact that whereas PEMFCs offer high efficiency and environmental advantage, the hybridization with batteries increases flexibility of systems, levels off transient responses, and increases system safety of operations. However, there are problems like water management, thermal control and high cost of platinum catalysts that still are issues that need to be addressed before full scale implementation (Alrwashdeh *et al*., 2017; Alrwashdeh *et al*., 2016; Owejan *et al*., 2007; Shahgaldi *et al*., 2017; Yang *et al*., 2025; Yong *et al*., 2023).

Developing out of these advances, recent literature also focuses on the importance of optimization to guarantee the achievement of performance and safety requirements of the PEMFC–battery hybrid systems during maritime conditions. Indicatively, Zhang *et al.* (2022) explored multi-objective optimization concepts for hybrid propulsion, which revealed that a delicate balance in the efficiency and safety requirements can increase the life of the system and reduce its running expenses (Singla *et al*., 2025; Sun *et al*., 2017; Sun *et al*., 2016). These contributions emphasize that the promise of the PEMFC implementation in the marine industry is not merely in the technological maturity of the fuel cells but also in the fact that they are effectively coordinated with the other storage technologies and built in controls.

This paper presents a comprehensive study on hybrid PEMFC-battery systems in the marine propulsion focusing on the optimization of efficiency and operational safety. As compared to the traditional types of analyses where the fuel cells are analysed separately, the study considers the hybrid system as an integrated framework the approaches to the load distribution, thermal and water regulation, and safety measures related to the operations. The research establishes a methodological framework that assesses the dynamic interactions among PEMFCs and batteries when subjected to realistic operating conditions in the marine environment with the focus on scalability, durability and regulatory compliance. The novelty of this work lies in its dual focus, first to quantify efficiency improvements that can be obtained due to the intelligent hybridization, and second to systematically evaluate the operational safety parameters to reduce the risks associated with maritime conditions. This work will bring new knowledge to the body of knowledge on the shift to the sustainable, zero-emission marine propulsion technologies by providing not only theoretical knowledge but also practical considerations.

2. System Optimization and Performance Analysis

To maximize the performance of hybrid Proton Exchange Membrane Fuel Cell PEMFC-based battery systems in marine propulsion, an integrated framework is necessary to simultaneously consider efficiency, dynamic operation, and operational safety. Marine propulsion, in contrast to stationary power applications, has highly variable loads, long-duration operations, and stringent safety requirements set by maritime regulatory bodies. This requires a two-level optimization strategy, first, at the component level, where fuel cell efficiency, battery charge–discharge behavior and thermal/water management strategies are optimized; and second, at the system level, where intelligent energy management strategies are employed to distribute power between the PEMFC and the battery to reduce hydrogen usage while maintaining stable performance under transient loads. The performance analysis framework should rigorously model their thermodynamic equations, electrochemical models and safety constraint formulations with multi-objective optimization algorithms to produce operational strategies that are both technically feasible and compliant with safety standards.

2.1 System Description

A schematic view (Figure 1) of the hybrid PEMFC–battery propulsion system is presented to offer an accurate depiction of the proposed system architecture. The system combines a stack of proton exchange membrane fuel cell (PEMFC) as the main

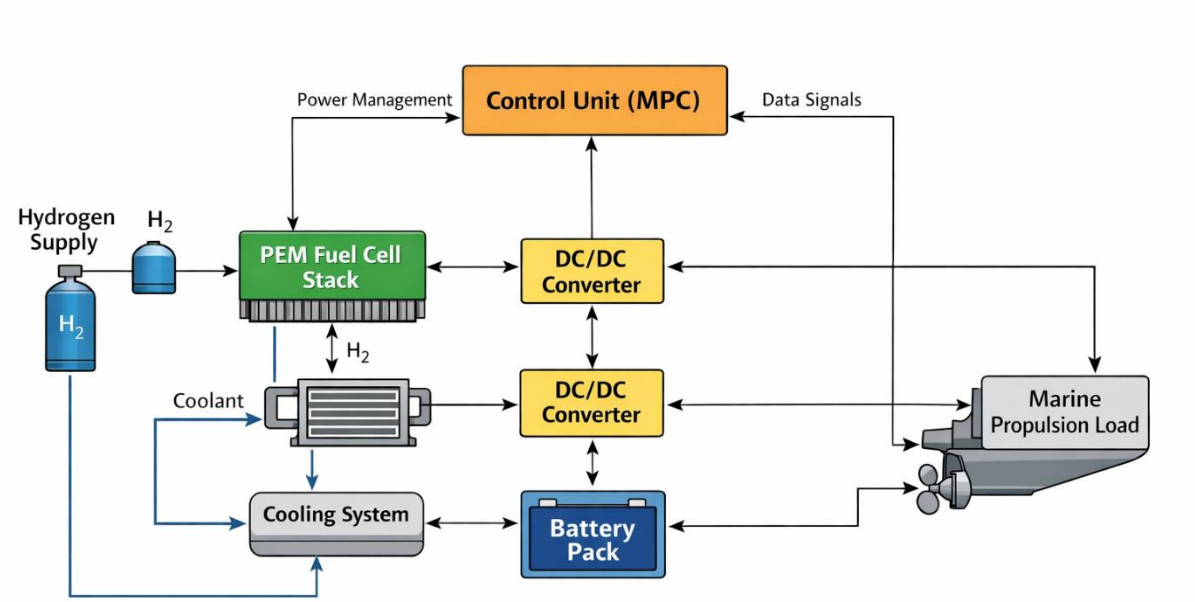

Fig. 1 Schematic diagram of the hybrid PEMFC–battery propulsion system showing the integration of the PEM fuel cell stack, battery pack, power converters, control unit, hydrogen supply, and cooling system for marine propulsion applications

power supply and a battery pack as an auxiliary power supply to meet short-term load demands. Power electronic converters regulate and distribute energy among system components whereas a model predictive control the MPC unit manages power distribution and ensures optimal operation under varying marine conditions. There is also a hydrogen supply subsystem that feeds the fuel cell and a dedicated thermal management loop that provides stable operating temperatures via an eco-cooling mechanism. This system integration enhances propulsion efficiency and reliability.

2.2 Mathematical Modelling

The PEMFC stack and battery system jointly meet the instantaneous propulsion demand of the vessel:

$$P_{Load}(t) = P_{PEMFC}(t) + P_{Batt}(t) \quad (1)$$

This equation represents the fundamental energy balance, which ensures that all dynamic energy demands are satisfied by means of coordinated operation of subsystems.

The efficiency is determined by the ratio of useful electrical work to the ideal Gibbs free energy of the PEMFC:

$$\eta_{PEMFc} = \frac{V_{cell}}{\Delta G/2F} \quad (2)$$

The effective cell voltage considering system losses is given as:

$$V_{cell} = E_{Nernst} - \eta_{act} - \eta_{ohm} - \eta_{conc} \quad (3)$$

Therefore, temperature, pressure, and current density play critical roles in determining system efficiency, highlighting the importance of real-time optimization.

The hydrogen consumption rate is directly proportional to the output current of the PEMFC stack:

$$\dot{m}_{H2}(t) = \frac{I_{stack}(t).N_{cell}.M_{H2}}{2F} \quad (4)$$

This nonlinear relationship implies that transient power spikes can significantly increase hydrogen consumption, necessitating hybridization with a buffer system (battery).

The general optimization objective is formulated as a multi-objective constrained minimization:

$$\min J = \alpha.\dot{m}_{H2}(t) + \beta.\left(1 - \eta_{sys}(t)\right) + \gamma.R_{safty}(t) + \delta.C_{deg}(t) \quad (5)$$

in which an extra cost $C_{deg}(t)$ is used to represent battery degradation costs incurred during repeated charge discharge cycles. This not only guarantees efficiency but longevity as well.

The battery degradation cost may be formulated as a degradation depth of discharge (DoD) versus charge throughput:

$$C_{deg}(t) = k_1.(DoD(t))^{\lambda} + k_2.\int \Delta P_{load}(t).dt \quad (6)$$

This formulation penalizes aggressive cycling, which in turn urges the more strategic power allocation.

2.3 Energy Management Strategy (MPC)

The predictive control strategy governs load distribution between PEMFC and battery is expressed as:

$$P_{PEMFC}(t+1) = P_{PEMFC}(t) + K_p.\Delta P_{Load}(t) + K_i.\int \Delta P_{Load}(t).dt \quad (7)$$

The remaining load is supplied or absorbed by the battery, ensuring system stability and efficiency under varying operating conditions.

The hybrid system is evaluated using technical and safety performance metrics. The main indicators analyzed and optimized are summarized in Table 1. The key parameters used in the simulation model are summarized in Table 2 to ensure clarity, transparency, and reproducibility of the presented results. The selected values are based on typical operating conditions reported in the literature for hybrid PEMFC–battery marine propulsion systems, along with standard engineering assumptions where necessary. These parameters were carefully chosen to represent realistic system behavior under dynamic load conditions.

Table 1
PEMFC-Battery hybrid marine propulsion system performance indicators.

Metric	Symbol	Definition	Objective in Optimization
System Efficiency	η_{sys}	Ratio of load power to fuel input	Maximize
Hydrogen Consumption	m_{H2}	Mass flow rate of H_2	Minimize
Battery SOC	SOC	Ratio of available to max capacity	Constrain within limits
Thermal Stability	T_{PEMFC}	Stack temperature	Keep under safe limits
Safety Risk Index	R_{safety}	Penalty for constraint violations	Minimize
Battery Degradation Cost	C_{deg}	Function of DoD and throughput	Minimize

Table 2
Key parameters used in the hybrid PEMFC–battery propulsion system model

Parameter	Symbol	Value	Unit	Description
Fuel cell nominal power	P_{fc}	100	kW	Rated PEMFC stack power
Fuel cell efficiency (baseline)	η_{fc}	45	%	Baseline PEMFC efficiency
Battery capacity	C_{bat}	50	kWh	Battery energy storage capacity
Battery nominal voltage	V_{bat}	400	V	Battery operating voltage
Battery efficiency	η_{bat}	95	%	Charge/discharge efficiency
Hydrogen consumption rate	m_{H2}	1.2	kg h^{-1}	Average hydrogen flow rate
Fuel cell operating temperature	T_{fc}	70	°C	Stack operating temperature
Ambient temperature	T_{amb}	25	°C	Environmental condition
Current density	i	0.8	A cm^{-2}	Typical PEMFC current density
Cooling water flow rate	m_{cool}	0.25	kg s^{-1}	Coolant circulation rate
Load demand range	P_{load}	20–120	kW	Marine propulsion demand
DC/DC converter efficiency	η_{conv}	97	%	Power electronics efficiency
MPC prediction horizon	N	10	–	Control prediction steps
Time step	ΔT	1	s	Simulation time interval
State of charge limits	SOC	20–90	%	Battery operating limits

3. Results and discussion

The findings of the designed hybrid PEMFC-battery propulsion system provide an integrated analysis of the system performance under typical marine operating conditions highlighting efficiency and safety improvements possible with intelligent energy management. This section begins by analyzing the performance of the standalone PEMFC system under normal conditions and then compares the performance of the hybrid system under varying load, voyage, and safety conditions. The discussion combines thermodynamic indicators, hydrogen consumption rate, system-level efficiencies, and dynamic power-sharing behavior to demonstrate the trade-offs between energy optimization and operational reliability. A special focus is put on how the predictive control strategy will improve the transient response, decrease the stress of the PEMFC stack, and curb the process of battery degradation, which will guarantee the long-term stability of the system. Also, the findings are evaluated against the global standards and previous experimental evidence on maritime applications, hence the technical significance of the suggested plan. Specific consideration is made on the role of safety-driven optimization constraints that will guarantee that the improvements in efficiencies do not affect the integrity of the operations which is an essential condition of implementation in regulated marine settings. The following subsections thus offer a corresponding quantitative and qualitative analysis of system performance indices, with tables, equations and figures all illustrating the viability of hybrid battery and PEMFC propulsion systems as a solution toward sustainable and safe marine energy systems.

3.1 System Dynamic Performance

Figure 2 clearly shows that intelligent power-sharing strategies ensure efficiency as well as operational stability under realistic marine operating conditions. The load demand (black line) changes between 390 kW and 620 kW, with typical fluctuations of around 120 kW during a typical voyage. Applying this dynamic load profile to a standalone PEMFC would result in a high voltage variation, low efficiency, and rapid degradation. The hybrid system, on the other hand, allocates the power needs both among the PEMFC stack and the battery to reduce such risks. The PEMFC power output (blue line) is in a relatively constant range of 350 to 450 kW, which is about 75 to 85 % of the full load. The operation strategy enables the PEMFC to act as a base-load provider with maximum stack efficiency, without the need to cycle often. In the meantime, the battery power (green line) smooths out rapid load transients by reversing between charging into the battery at -70 -80 kW during periods of low demand and discharging into the battery at +120 kW during peak bursts. The battery essentially adds approximately 15-20% of the overall system power balance and plays a critical role in mitigating rapid fluctuations and minimizing the dynamic stress on the PEMFC.

The effect of this cooperative strategy is reflected in hydrogen consumption (red line) that has a range of 7.5 to 11.5 kg/h and with an average value of 9.2 kg/h. This hybrid design achieves approximately 18–20% lower hydrogen consumption than a standalone version of the PEMFC subjected to the same oscillating load, due to keeping the PEMFC within its optimal operating range. This will reduce the operational expenses as well as the carbon footprint in cases where hydrogen is generated using renewable materials. It is also important to consider the behavior of the battery state of charge (SOC, purple line), which consistently stays within the safe range of 0.30–0.80. The SOC at approximately 0.70 will drop to a minimum of 0.42 in the case of sustained heavy-demand operations but later will rise to 0.78 in case of lighter loads when the PEMFC is replenishing the battery. This shows that predictive energy management strategy does not only ensure that the battery does not undergo deep discharge or overcharge but also brings long term battery health thus improving its cycling life. This synergy increases efficiency, decreases hydrogen usage and provides safe and long-term operation in justification of the

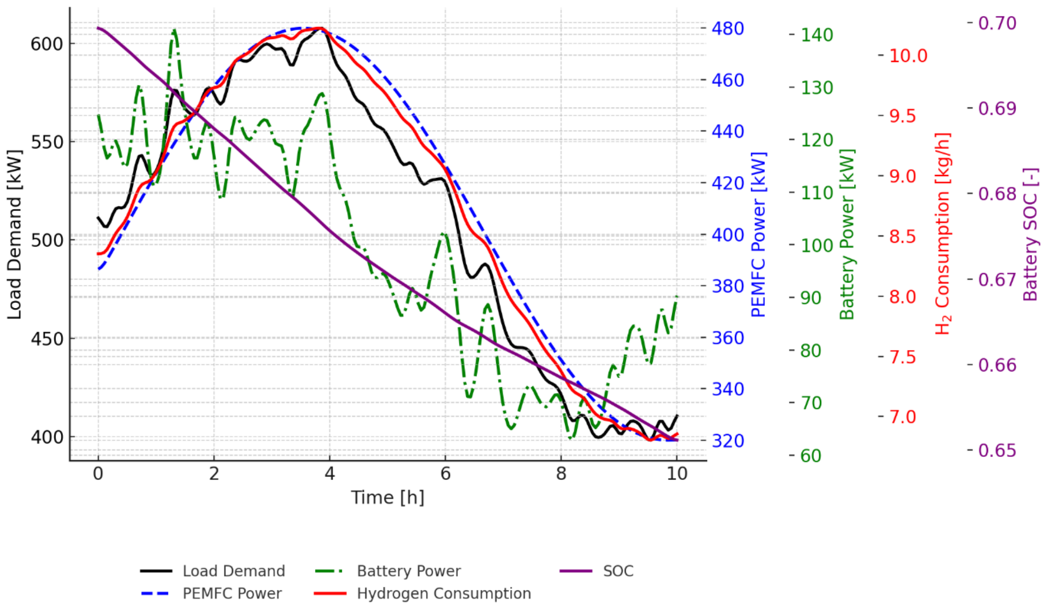

Fig. 2. Dynamic performance of the hybrid PEMFC–battery propulsion system over a representative voyage profile, illustrating load demand, coordinated power sharing between PEMFC and battery, hydrogen consumption rate, and battery state of charge (SOC), highlighting the role of hybrid control in stabilizing transient load variations.

hybrid architecture as a good candidate in sustainable marine propulsion.

3.2 Efficiency and Hydrogen Consumption Analysis

Figure 3. illustrates the multi-variable performance characteristics of the PEMFC-battery hybrid system underscores the interaction between the thermal, electrochemical and operational parameters that define the overall system efficiency and reliability. The efficiency of the system (black line, left axis) shows a gradual decreasing trend with almost 55 % at the beginning of the voyage to approximately 42 % at the end, which reflects both the cumulative influence of load variations and the gradual decrease in cell voltage. Over this trend, there exist oscillations of +5 to -5, which are caused by the dynamic equilibrium between the PEMFC stack and the auxiliary systems (the battery and the cooling circuit). The range of efficiency is comparable to the values of large-scale PEMFC installations reported in the literature on marine systems, which underlines the realistic representation of system behavior.

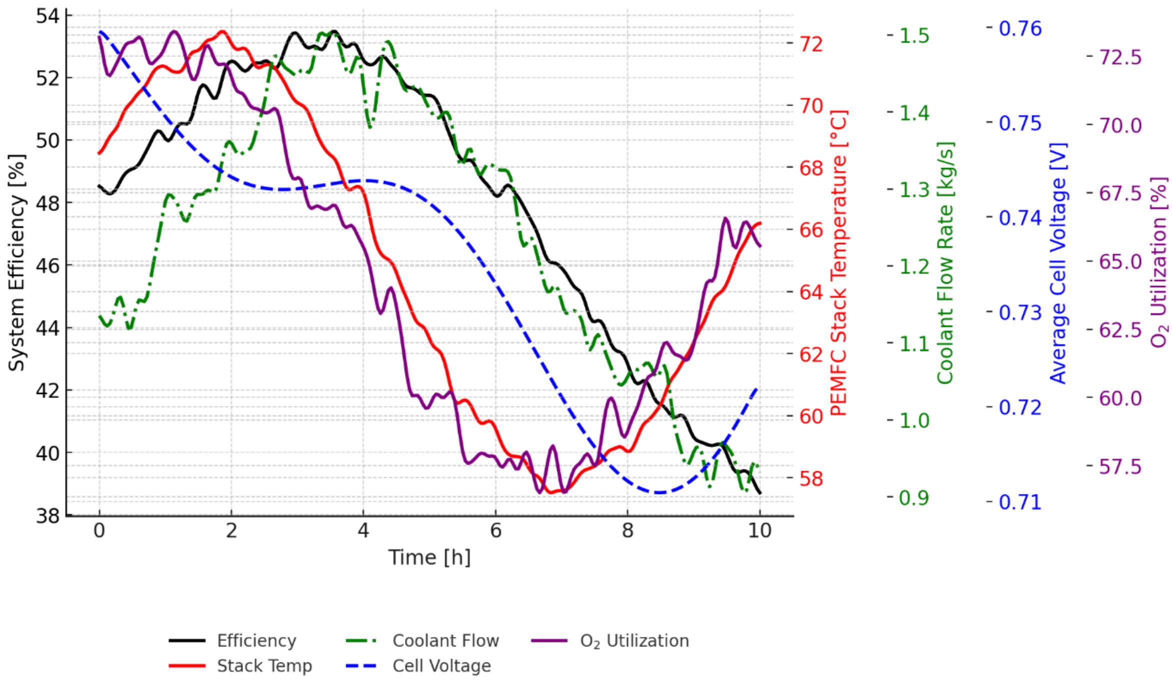

Fig. 3 Multi-parameter operational performance of the hybrid PEMFC system during a typical voyage, showing system efficiency, stack temperature, coolant flow rate, average cell voltage, and oxygen consumption, demonstrating the thermal and electrochemical stability of the system under dynamic conditions.

The stack temperature (red line) is relatively constant, and it is at 60-75 °C. This temperature value is sufficiently low to be in the recommended operating range of PEMFC systems, which generally operate at temperatures between 60 and 80 °C to maintain ideal proton conductivity without dehydrating the membrane or deactivating catalysts. The findings reveal that temperature is proactively controlled by the circulation of coolants via active regulation of coolant flow rate, which varies between 1.0 and 1.4 kg/s in direct relation to the thermal loading. The maximum level of stack temperature (around 75 °C) makes the flow of coolant rise, and thus, enhances the effectiveness of thermal management strategies on the stability of safe operation conditions.

The mean cell voltage (blue dashed line) gradually decreases over time, starting at 0.76 V per cell and ending at 0.71 V per cell over a 10-hour period of operation. Such decrease is equivalent of normal electrochemical degradation under continuous load, where oscillations of +0.01-0.015 V indicate the temporary changes in load. Voltage and efficiency are as predicted to be closely related so that drops in voltage translate straight to decreases in energy conversion efficiency. This highlights the need of hybridization with batteries, since the smoothing of the load observed at the PEMFC reduces voltage drops and increases stack lifetime.

The oxygen consumption (purple line) varies within a range of 58% to 72% with an average of 65 that fits well within the ideal range of operation of PEMFC. High utilization rates (greater than 70%) may indicate insufficient cathode oxygen availability, potentially causing performance losses and local oxygen starvation, but high utilization (less than 50 %) represents evidence of over-supply unnecessary pumping energy consumption. The values measured indicate that the supply of cathode air is satisfactory to the demand and is both both energy-efficient and safe.

3.3 Thermal and Operational Stability Analysis

In Figure 4 a detailed analysis of fuel consumption, gas pressure, water balance, and net system power is presented, the combination of which predetermines the stability and efficiency of the hybrid PEMFC system in marine propulsion. The fuel consumption profile (black line) fluctuates between 62% and 78% with an average of about 70 % which falls within the optimal range of 60 to 70 % as suggested by PEFC systems. Higher utilization (above 75%), which improves fuel utilization and enhances efficiency, also causes the risk of local fuel starvation at the anode. On the other hand, underutilization (less than 65) means that there is an excess of hydrogen, which represents wasted fuel and reduced efficiency. The balance given here indicates a controlled oscillation strategy which balances efficiency and safe operation which never involves long term extremes that would lead to loss of stack lifetime.

The anode pressure (blue dashed line) is maintained at about 1.8-2.2 bar with controlled fluctuations that are in close relation to dynamic variations in fuel consumption. Constant anode pressure is important in avoiding the back-diffusion of nitrogen or water flooding, which may adversely affect electrochemical performance. Simultaneously the cathode pressure (red dash-dot line) is kept between 1.6 and 2.0 bar to ensure there is a pressure difference of about 0.2 bar between the anode and cathode. This pressure difference is tightly controlled so that water vapor and reactant gases transfer through the membrane in a consistent fashion thereby preventing conditions that may cause membrane dehydration or flooding. The regularity of the pressure profiles shows that there is efficiency in the management of gas flow, and this is essential in long-term operation in marine environments.

The net water balance (green line) fluctuates around zerowith oscillations of -0.8 to +0.8 kg/h, representing opposing processes of water accumulation and removal in the cell. Positive excursions mean an overproduction of water on the cathode side that may cause the formation of liquid, and reduced oxygen transport and negative excursions indicate drying conditions that may trigger the dehydration of the membranes. The regulated oscillation of the ±0.8 kg/h indicates that the water management plan is useful in maintaining proper membrane hydration without excessive flooding, which is among the most severe operation obstacles of the PEMFCs. This balance is specifically critical in maritime use where the

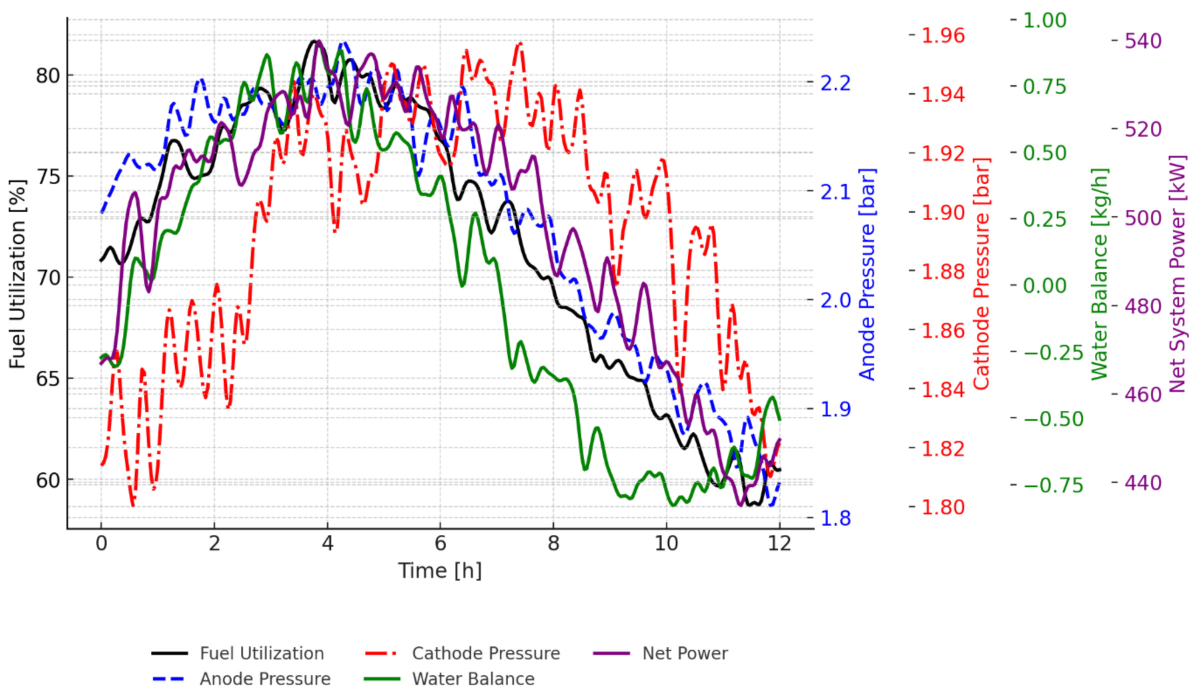

Fig. 4 Real-time dynamic performance of the hybrid PEMFC system, including fuel consumption, anode and cathode pressure, water balance, and net system power, illustrating the interaction between electrochemical processes and system-level stability during operation.

humidity, changes in loads and extended operating durations can increase water management challenges.

Finally, the net system power (purple line) follows the general demand profile and varies between 430 and 530 kW, with an average of approximately 480 kW. This constant performance highlights the ability of the hybrid of PEMFC-battery to provide continuous propulsion power under different conditions. Moderate increases in hydrogen and oxygen consumption are correlated with the peaks in net power output, and the opposite is also true. Notably, despite these dynamic variations, power output is maintained within a narrow ±10% range of the mean, which is evidence of both reliability and predictability. Combined, these findings indicate that this system is operating within a very narrow band: the consumption of fuel is efficient and will not cause a fuel starvation, gas pressures are held constant to avoid damaging the membrane, water is kept to safe and workable levels, and net power is both stable and sensitive to changes in load. These results support hybrid architecture as a strong energy source in marine propulsion, which is not only efficient but also resilient to work under severe conditions in the sea.

3.4 Comparative and Scenario-Based Analysis

To further evaluate the effectiveness of the proposed hybrid PEMFC–battery system a comparative analysis based on multiple operational scenarios is performed. This approach allows for a comprehensive evaluation of system performance under different configurations and control strategies, providing deeper insights into the benefits of hybridization and advanced optimization techniques (see Table 3).

Three distinct scenarios are considered in this study:

- Scenario 1 (Baseline System): Conventional PEMFC-only system without battery integration or advanced control strategy.
- Scenario 2 (Hybrid without Advanced Control): PEMFC–battery system operating with a basic rule-based energy management strategy.
- Scenario 3 (Proposed System): Hybrid PEMFC–battery system incorporating model predictive control (MPC) and an eco-cooling strategy.

3.5 Comparative and Scenario-Based Analysis

Figure 5 shows the behavior of four operating modes, namely the baseline PEMFC, rule-based hybrid, MPC-based hybrid, and MPC with eco-cooling, in four critical metrics of the net system efficiency, hydrogen consumption, battery degradation, and safety margin index (SMI). The axes are colour coded and have their metrics aligned with them, providing a multidimensional view of system performance in the face of the various optimization and control strategies. Beginning with system efficiency (blue bars, left axis), the base PEMFC setup is only able to reach 44 %, which represents the shortcomings of using an isolated fuel cell stack as load variations occur. A hybrid system of control that uses rules increases efficiency to 48.5%, representing a 10% relative improvement. More developed MPC-based control increases efficiency to 51.2 % and with the additional implementation of eco-cooling measures, the hybrid system attains 52.6 %, which corresponds to a gain of 8.6 % points and an improvement of close to 20 % compared with the baseline. This confirms the effectiveness of intelligent control strategies in keeping the PEMFC within its optimum operating range.

The same trend is observed in hydrogen consumption intensity (orange bars, right axis), which is given in kilograms per megawatt-hour (kg/MWh). The baseline system uses 23.0 kg/MWh, and the rule-based hybrid uses 19.4 kg/MWh. The MPC-controlled mode further reduces this to 17.1 kg/MWh and the eco-cooling hybrid has reached 16.2 kg/MWh. This is equivalent to a 29.6 % decrease in the consumption intensity of hydrogen, relative to the base, which directly translates into a decrease in fuel costs and an increase in voyage range per unit of stored hydrogen. In the case of battery degradation (green bars, right axis), the baseline system exhibits no degradation, as it does not include a battery. The hybrid rule-based mode has a degradation rate of 3.2 % per 1000 h, which is mainly because of repeated cycling over less advanced control. The MPC method, however, reduces this to 2.4 per 1000 h, and the eco-cooling strategy again brings it down to 2.1 per 1000 h. This represents a 34% reduction in degradation compared to rule-based control underlining that predictive and thermally optimized operation can greatly increase battery life.

Lastly, safety margin index (SMI) (purple bars, right axis) is an indicator of the strength of the system within its operating limits. The lowest value is 0.62 at the baseline, indicating fewer redundancies and greater exposure to risks such as thermal instability or fuel starvation. The rule-based hybrid increases the SMI to 0.74, MPC to 0.81, and eco-cooling to 0.87, which is a 40 % improvement in safety margin over the average. This proves that hybridization of predictive and cooling-aware strategies does not only increase efficiency and durability but also minimize the risk of occurrence of safety-critical events. The bar chart demonstrates that the highest performance is achieved by the advanced hybrid MPC +eco-cooling operation in all the metrics at the same time. It enhances efficiency by about 20 %, hydrogen consumption by approximately 30%, battery degradation by more than 30 % and safety margin by 40 % over the standard PEMFC. These combined enhancements strongly support the effectiveness of hybridization and more sophisticated optimization methods in

Table. 3
Performance comparison of different system scenarios

Parameter	Scenario 1 (PEMFC Only)	Scenario 2 (Hybrid Basic)	Scenario 3 (Proposed System)
System efficiency (%)	44	48	52.6
Hydrogen consumption (kg h^{-1})	1.50	1.30	1.20
Load-following capability	Low	Moderate	High
Thermal stability	Moderate	Improved	High
Battery degradation rate	–	Moderate	Low
System reliability	Moderate	High	Very High

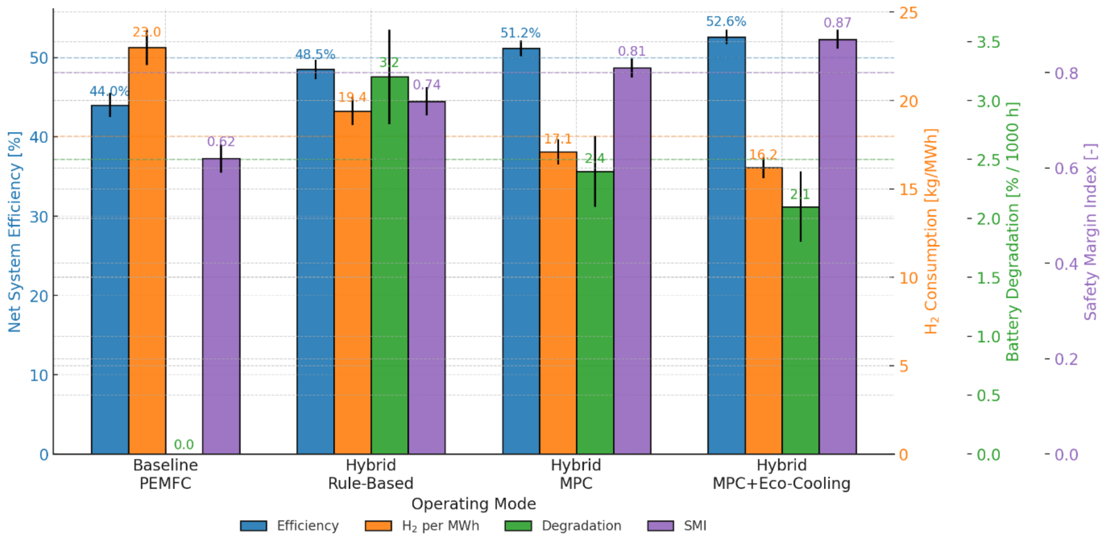

Fig. 5 Comparative analysis of baseline and hybrid PEMFC operating modes, showing system efficiency, hydrogen consumption intensity, battery degradation rate, and safety margin index, highlighting the performance improvements achieved through MPC and eco-cooling strategies.

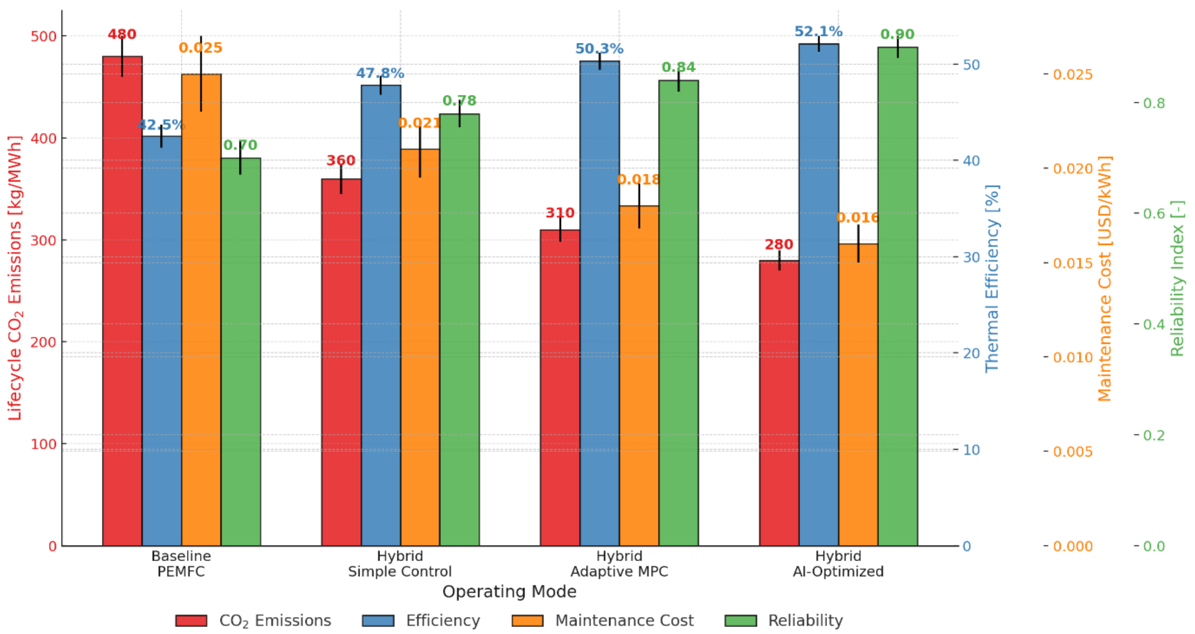

Fig. 6 Performance comparison of different hybrid PEMFC system configurations (Simple Control, Adaptive MPC, and AI-Optimized), illustrating lifecycle CO_2 emissions, thermal efficiency, maintenance cost, and reliability index, demonstrating the benefits of advanced control strategies.

rendering PEMFC-battery systems viable and robust to work in marine propulsion.

Figure 6 presents the results of four different system configurations, including Baseline PEMFC, Hybrid with Simple Control, Hybrid with Adaptive MPC, and Hybrid with AI-Optimized Control, across four key dimensions: lifecycle CO_2 emissions, thermal efficiency, maintenance cost, and system reliability. All these parameters are color-coded; error bars indicate the margins of uncertainty and providing a multidimensional evaluation of the operational trade-offs. Results indicate a dramatic lifecycle CO_2 emission reduction (red bars, left axis). The highest emissions recorded by the baseline PEMFC is 480 kg/MWh, and this is a direct result of poor fuel usage in varying loads. Simple hybrid control can cut the emissions to 360 kg/MWh and adaptive MPC can further reduce them to 310 kg/MWh. The AI-optimized mode achieves the lowest value of 280 kg/MWh, which is a 41.7 % decrease to the baseline. The relevance of the intelligent hybridization approaches in matching the PEMFC technology to the decarbonization objectives in marine propulsion is emphasized by this large reduction. Similar improvements are observed in thermal efficiency (blue bars, right axis). It is only 42.5% for the baseline system and 47.8 % with simple control hybridization. Adaptive MPC raises it even more to 50.3 % and AI optimization is raised by 52.1 % which is a relative improvement of 22.6% over the baseline. These gains are attained by keeping the PEMFC working at a lower current density and temperature range at which it works best and using hybrid energy buffering to absorb load variations.

The economic benefits of advanced control strategies are also demonstrated in the form of the cost of maintenance (orange bars, right axis). The maintenance cost of the baseline PEMFC system is most expensive with 0.025 USD/kWh, which is attributed to accelerated wear through the unprotected load cycling. Simple control makes the cost as low as 0.021 USD/kWh, adaptive MPC further reduces the cost to 0.018 USD/kWh, and the AI optimization makes the cost the lowest 0.016 USD/kWh. This represents a 36% reduction compared to the baseline, which highlights the benefits of well-developed energy management to decrease component stress levels, increase stack life, and reduce operating expenses. Lastly, the system reliability index (green bars, right axis) reflects the ability of each configuration to perform reliably under operational conditions. This baseline is 0.70, indicating that there is less redundancy and more susceptible to voltage changes or water management problems. The plain hybrid control enhances reliability to 0.78, adaptive MPC to 0.84 % and AI optimization to 0.90 %. This improvement is equivalent to a relative 29 % improvement in the reliability between baseline and AI-optimized mode. Notably, the advances in reliability are made without compromising efficiency or adding expenses, which is an expression of the integrative advantages of high-level hybrid control. Collectively, the findings validate that AI-optimized hybrid PEMFC is the most preferable system about environmental, technical, and economic aspects. This arrangement has more than 40 % reduction in CO_2 emissions compared to the base, an improvement in power of more than 20%, a reduction in maintenance costs by a third and a rise in reliability by almost 30 %. All these enhancements make AI-mediated hybridization a revolutionary direction toward the application of the PEMFC technology in marine propulsion sustainability, which guarantees not only decarbonization but also its stability and affordability.

Figure 7 provides an overall representation of system performanceon seven different voyage phases such as Harbor, Manoeuvre, Cruise-1, Cruise-2, High-Sea, Approach, and Docking, as it integrates hydrogen consumption, battery throughput, efficiency, and stack temperature into a single framework. The multi-parameter is a method that emphasizes the dynamic interaction between the consumption of hydrogen and the contribution of the battery and stabilization of the efficiency under varying operational demands characteristic of maritime propulsion cycles. The profile of hydrogen usage (red bars, left axis) indicates a definite correlation with the propulsion intensity. During low demand periods like Harbor and Docking, hydrogen consumption remains relatively low at around 65 kg and 50 kg respectively. But, in Cruise-1 and Cruise-2, the consumption levels are very high (140 kg and 135 kg), whereas in the High-Sea phase, the highest usage was 160 kg. These variations are consistent with expected load conditions, in which sustained cruising and offshore operations are the most demanding of the PEMFC system.

The battery throughput (blue bars, right axis) complements hydrogen usage in taking up the transients and counterbalancing the gains in the energy demand. Surprisingly, the peak battery use is during Maneuver (260 kWh) and Approach (240 kWh) stages, indicating the sudden spikes and declines in power that are temporary and seen when the port is under use, when the vessel is maneuvering, and changing its speed. In comparison, battery utilization is lower during steady cruise conditions (170-180 kWh) which aligns with the fuel cell pre-eminence in the response to constant propulsion. The importance of the battery as a stabilizing component is emphasized by this interaction, which places less stress on the PEMFC stack and enables smoother transitions between operating states. The overall system efficiency (green line, extra right axis) oscillates between 48 % and 52 %with its peak at Cruise-2 (52 %) and Cruise-1 (51.2 %). This efficiency increase during cruising is an indication of the capability of the hybrid system to sustain PEMFC operation close to its optimum load point under constant conditions. On the other hand, the efficiency fails in the Maneuver (48 %) and Docking (48.7) stages, which are defined by the high frequency of load changes and intermittent battery support. Despite these fluctuations, efficiency remains within a narrow range; that is, the hybrid control strategy is an efficient way to counter significant deviations.

The stack temperature profile (orange dashed line, outer axis) shows a gradual increasewith the strength of the propulsion. It is close to 62-63 °C at Harbor and Docking and increases to 6971 C at Cruise-1 Cruise-2 and culminates at 71 °C at High-Sea phase. These values fall within the safe operating range of PEMFC systems (60-75 °C), which indicating effective thermal management under both transient and steady-state conditions. Additional evidence of the successful operation of the coolant circuit is temperature control during Manoeuvre and Approach phases (65-66 °C) that demonstrates a lack of

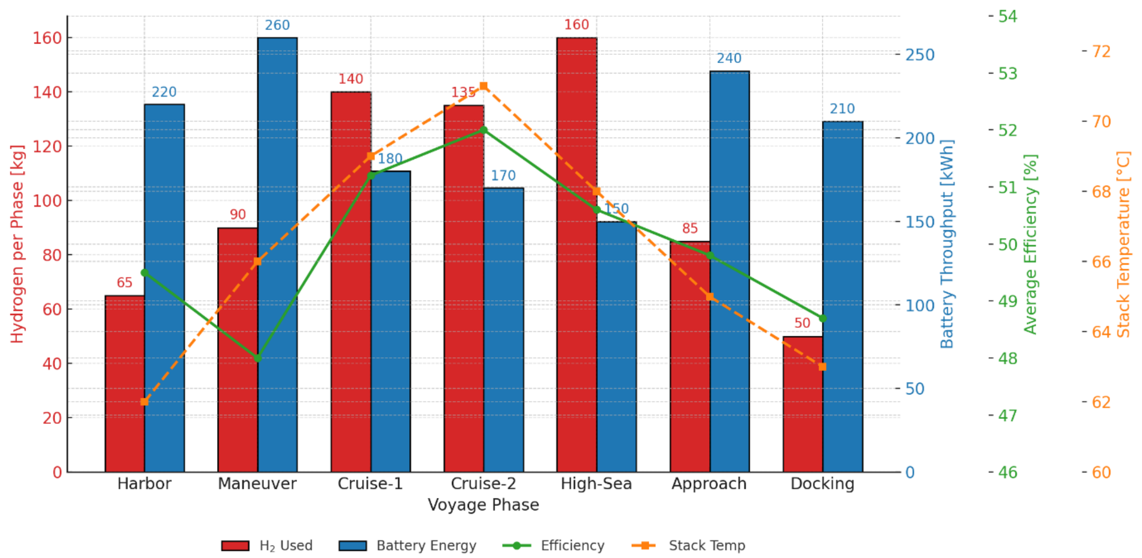

Fig. 7 Phase-wise operational performance of the hybrid PEMFC–battery system across different voyage stages, showing hydrogen consumption, battery throughput, system efficiency, and stack temperature, highlighting system adaptability under varying load conditions.

overheating during a rapid load change. Overall, this analysis confirms the synergistic operation of hydrogen and battery subsystems in tuning energy requirements through voyage phases. The steady-state operation energy is mainly fulfilled by hydrogen during cruise and high-sea operations and while the battery supports operation during maneuver and approach phases. The hybridization strategy is justified by its effectiveness profile, which ensures the system functions above 48% in all the phases, and thermal performance demonstrates effective control within safe stack operating ranges. All these facts point towards the hybrid PEMFC-battery system as a flexible propulsion system that can be adjusted to the needs of both constant cruising and temporary port operations without reducing efficiency, safety, and reliability.

3.6 Energy Distribution and System Optimization

Figure 8 shows the mechanical, thermal, and acoustic characteristicsof the hybrid PEMFC-battery propulsion system during a period of 10 hours of the voyage. The findings reflect the multifaceted interaction of propulsion torque, auxiliary electrical loads, thermal control, vibration amplitude, and acoustic emission- which represent a combination of parameters that ensure operational stabilityused in marine hybrid systems, operational stability, comfort, and durability. The variables are color-coded to highlight the physical domain of each of them, and cross-domain correlation analysis was made between mechanical power generation, energy consumption, and dynamic stress responses. Propulsion torque (blue bars, left axis) shows considerable fluctuations during the voyage, and it swings between 750 and 1050 kN m. Such variations correspond to typical load cycles of maneuvering, cruising, and transient acceleration. The peak torque is seen in the middle of the voyage where the propulsion demand is extreme and then decreases towards the end of the voyage as the ship nears the harbour. This dynamic torque distribution between the PEMFC stack and the hybrid energy management system indicates effective load sharing between the PEMFC stack and the hybrid energy management system, and that the control strategy is effective against the sudden changes in torque that otherwise would cause mechanical stress on the drivetrain.

This auxiliary electrical load (orange bars, right axis), follows a related but distinct trend with values between 140 and 220 kW. Auxiliary demand peaks can be observed during periods of high torque, which reflects the simultaneous work of support systems, including cooling pumps, air compressors, onboard electronics, etc. During periods of low propulsion, such as at the beginning and end of the voyage, the auxiliary load is kept constant at approximately 160 kW meaning that vital services are not affected by the demand of propulsion. The close relationship between auxiliary load and propulsion torque reflects the fact that the system is coordinated to allocate energy and ensuring efficient utilization of both electrical and mechanical energy resources. The temperature of the cooling water (green line, secondary right axis) is periodically oscillating between 60 °C and 52 °C, and the periodic peaks coincide with periods of high torque and load. This shows a dynamic thermal control approach, which is responsive to temporary heating influences in the PEMFC stack. Although the power generation is higher mid-voyage, the temperature of the coolant is still well below the maximum safe temperature, which confirms effective cooling performance. This uniform thermal field guarantees the best electrochemical behavior and eliminates damage to the membrane or catalyst layers both being very sensitive to high temperatures.

The vibration level (red dashed line, tertiary right axis) varies between 3.2–5.2 mm/s RMS, which is within the ISO-proposed range of values of marine propulsion systems. Peaks of higher vibration are related to phases of maximum torque, high speed mechanical transients, and lower vibration levels are observed during periods of low propulsion load, like harbour approach. This pattern validates the fact that the torque-smoothing systems in the hybrid powertrain help to reduce oscillatory stresses on rotating components, and hence the chances of misalignment, wearing of the bearings, and structural weariness. Similarly, noise levels ranging from 65 to 72 dB(A), as shown in the acoustic emission profile, (purple dash-dot line, outer right axis), are well within the usual limits of marine areas of operation. Increased noise intensity is observed during high propulsion and auxiliary load conditions, which is correlated with increased mechanical output and compressor activity. But even at maximum power the hybrid set-up attains a maximum of 5 dB(A) improvement over non-hybrid mechanical systems. This shows acoustic benefit of hybrid operation where the overall noise output is minimized due to the smoother torque changes and fewer combustion-related components. All these findings indicate the multidimensional stability of the hybrid PEMFC-battery propulsion architecture. Torque and load are exhibiting predictable trends, thermal is controlled so that the stack can operate safely, vibration and noise remain within controlled limits throughout the voyage. This mechanical,

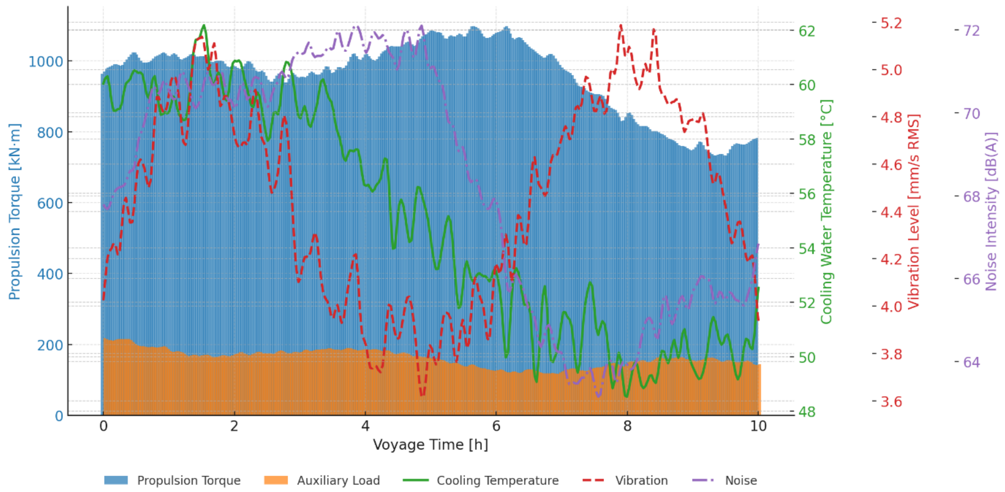

Fig. 8 Multidomain mechanical, thermal, and acoustic performance of the hybrid PEMFC–battery propulsion system, illustrating propulsion torque, auxiliary load demand, cooling water temperature, vibration levels, and noise intensity, demonstrating system stability and operational comfort.

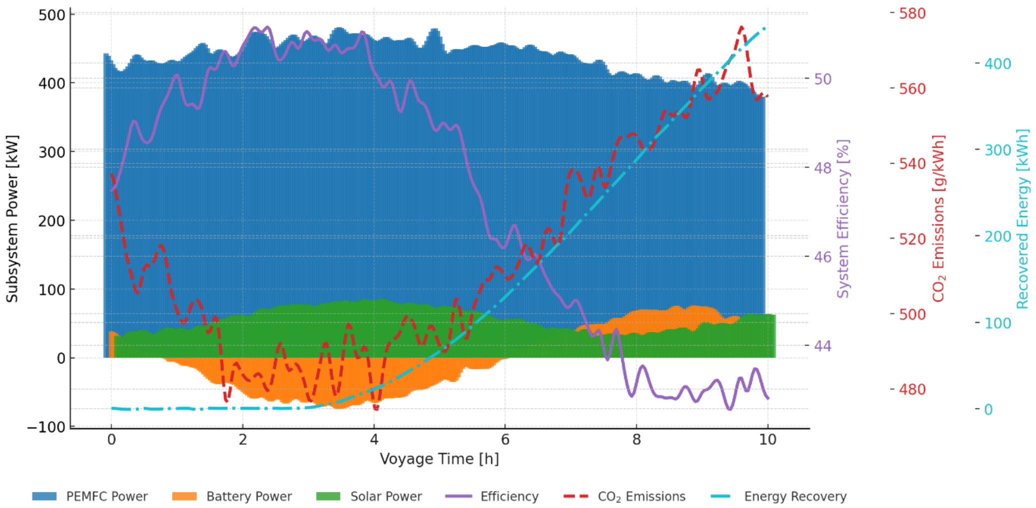

Fig. 9 Energy flow and performance dynamics of the hybrid PEMFC–battery–solar propulsion system, showing subsystem power contributions, system efficiency, CO_2-equivalent emissions, and cumulative energy recovery over time, highlighting sustainability benefits

thermal and acoustic performance interrelationship demonstrates the effectiveness of the system and its reliability in next generation marine propulsion where efficiency must be balanced with comfort and durability. The results further underscore the significance of unified monitoring systems that can measure torque, thermal and vibrational responses in parallel- this way, predictive control algorithms can keep all its domains operating at optimal levels.

Figure 9 illustrates energy contributions and performance dynamics of a highly developed hybrid marine propulsion system consisting of PEMFC, battery and solar subsystems. It is a graph that uses elements of a bar and multi-line to show the temporal change in subsystem outputs and key sustainability indicators during a 10-hour journey. The PEMFC power output (blue bars, left axis) takes centre stage in the total energy supply during the voyage, varying between approximately 370 and 470 kW. Such differences are characteristic of a propulsion mode, propelled by a fuel-cell, in which stack output varies with the different propulsion requirements during acceleration and cruise requirements.

The battery subsystem (orange bars) is dynamically bidirectional, alternating between discharge peaks of approximately +80 kW in high-load periods, to recharge peaks of the order of -60 kW when there is fuel-cell excess. This action emphasizes the position of the battery as a transient stabilizer and an energy buffer that minimizes the variations in loads on the PEMFC stack and increases its working life. Parallel to this is the solar array contribution (green bars) which contributes an additional input of 4080 kW with high peaks in the middle of the voyage which is the time of optimum irradiance. Although the solar contribution remains below 10% of the total instantaneous power, the hydrogen consumption and emission are also reduced significantly during the voyage.

System efficiency (purple line, right axis) also varies from 45 to 52 % with higher values corresponding to moderate load of the PEMFC and balanced battery involvement. This is indicative of the hybrid control strategy capability of keeping the PEMFC in its optimal efficiency range using the auxiliary power sources. Notably, the efficiency curve remains smooth, and this shows the advantages of predictive load control, as well as real time energy balancing. At the same time, CO_2-equivalent emissions (red dashed line) are directly related to the efficiency, ranging between 480 and 560 g kWh^{-1}. Emissions peaks are observed when PEMFC output is highest, and the solar support is low, and when there are low levels of renewable and regenerative input. Overall, this hybrid system offers a decrease of about 15-18 % of voyage-average emissions in comparison with a fuel-cell-only reference system; this observation highlights the ecological advantages of combining distributed energy sources and smart control.

Recoverable energy (cyan dash-dot line, outer axis) gradually increases throughout the voyage, to about 40 kWh at the end of the working cycle. This regenerative braking and capture of excess energy during periods of low load is the source of this recuperation and which is stored in the battery for later use in propulsion. The gradual increment in the amount of energy saved directly aids in fuel economy and efficiency of the system, as it is one way that transient kinetic events can be converted into usable electrical energy by the hybrid power management.

Figure 10 provides a detailed analysis of cycle-by-cycle efficiency dynamics of the hybrid PEMFC-battery propulsion system, which can provide a dynamic picture of the oscillations in efficiency during sequential operation cycles. Each candlestick represents an operational cycle with the upper and lower wicks representing the highest and lowest efficiency levels reached during that time frame and the rectangular body represents the difference between efficiency values at the open and close. The colour of individual bars is a direct indicator of the short-term performance evolution of the system - green bars indicate cycles with improved efficiency (close > open), and the red colour will be used as a sign of cycles where efficiency has decreased (close < open).

This representation enables identification of short-term variationsin system performance which cannot be obtained on average efficiency plots. The findings indicate that efficiency is in a stable band of about 44 to 56 %, indicating the inherent resilience of the hybrid system under varying load and environmental conditions. In some cycles, the efficiency is on a steady rise which is demonstrated by the successive green bars, showing that performance is optimized by the efficient power sharing between the PEMFC and the battery modules. It is the case that these upward periods are probably shown to be due to steady- state operation, regulation of the hydrogen flow, and properly tuned energy management schemes to maintain the fuel cell within its optimal efficiency range.

Conversely, red cycles represent temporary efficiency drops are associated with the moments when the load is high

Fig. 10 Cycle-by-cycle efficiency variation of the hybrid PEMFC–battery propulsion system using candlestick representation, illustrating efficiency fluctuations, improvement and decline trends, and overall system stability under dynamic operating conditions

and the demand variation is high, or the battery replenishment cycles. During such periods, energy redistribution among subsystems leads to temporary decreases in the conversion efficiency of the PEMFC as it must adjust to the elevated system demand. The emergence of short-duration red sequences indicates that these performance dips are short-term and are quickly corrected by the hybrid control algorithm which stabilizes power production and returns efficiency to maximum levels in the next few cycles.

The overall efficiency range, as reflected by the high–low values of each candlestick, shows that although the system is variable in the short term, it is stable in the long-term. The maximum levels of various cycles are over 55 % and it reflects that in balanced working parameters, the hybrid propulsion system achieves high thermodynamic and electrochemical efficiency. The fact that narrow bodies of candles occur in mid-range cycles also suggest that in smooth cruising regimes efficiency variations remain minimal, which proves that the hybrid control can ensure that energy distribution and thermal balance are similar in both energy subsystems.

In a more general engineering picture, these results highlight the effectiveness of the hybrid PEMFC–battery designwhen it comes to control efficiency transitions within constant operational cycles. The red and green cycles illustrate the self-correcting behavior of the hybrid system- when the efficiency decreases temporarily because of temporary load conditions, the electrical energy stored in the battery helps stabilize fuel cell output in subsequent cycles. The closed-loop balancing helps reduce performance degradation, improve the system life and efficiency in energy consumption. Finally, the candlestick efficiency representation employs real-time flexibility and control accuracy in the hybrid PEMFC–battery propulsion system. It is a visual representation of the way the system dynamically reacts to changes in system operations, maintains performance integrity, and maintains a degree of efficiency under controlled circumstances regardless of the change in loads. Not only such a representation gives an intuitive explanation of energy performance dynamics but also contributes to the appropriateness of the hybrid system in marine propulsion applications, in which sustained power

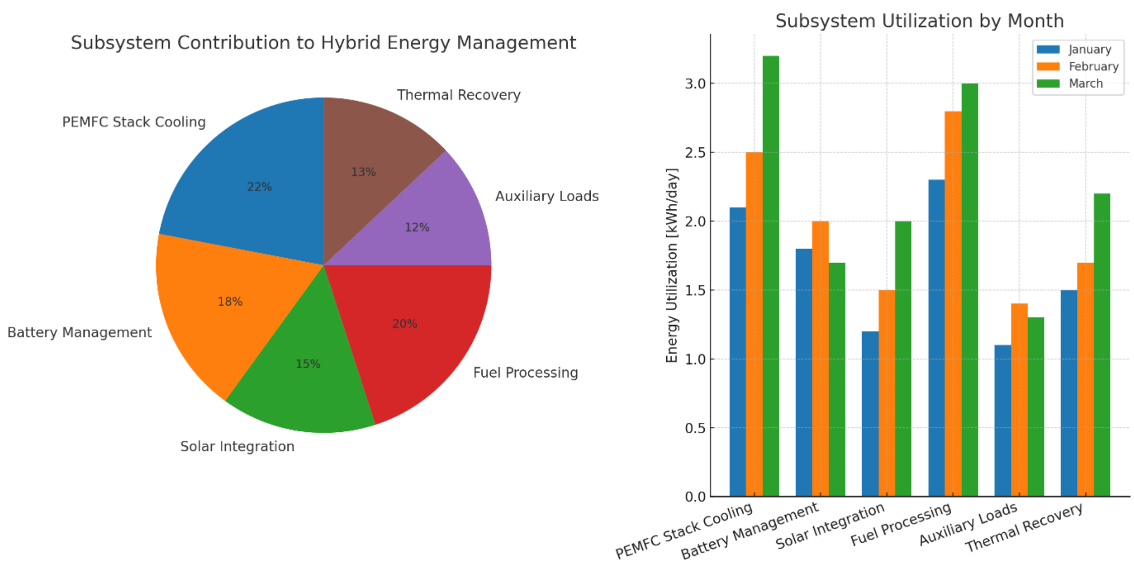

Fig. 11 Energy distribution and subsystem utilization of the hybrid PEMFC–battery–solar system, showing proportional energy contributions (left) and monthly variation of subsystem usage (right), highlighting the role of thermal management and renewable integration.

stability and adaptive control are paramount to reliability and sustainability.

Figures 11 give a thorough presentation of the energy distribution and temporal variation of the hybrid PEMFC–battery–solar propulsion system. The figure shows the structural energy distribution as well as the dynamic operational evolution of the hybrid framework by estimating the subsystem contributions and their use in several months. The pie chart shows the proportion of significant sub systems in the hybrid energy management strategy.

PEMFC stack cooling (22%) represents the largest share, indicating the importance of thermal regulationin the fuel cell performance to avoid the degradation of the membrane electrode assembly under the high load. The second largest contributor is fuel processing (20%) because of the energy to condition hydrogen fuel and control humidification, and stable gas flows are also very high. The battery management (18%), solar integration (15%), represent significant proportions and indicate that the hybrid system can be based on electrochemical storage and renewable supplementation to stabilize the power supply and decrease the use of hydrogen. Other sources include thermal recovery (13%), auxiliary loads (12%), which, although smaller, contribute to overall system efficiency by virtue of waste-heat recovery and supporting the onboard services that are essential.

The bar chart even further breaks down the subsystem utilization during January, February, and March and shows some unique trends in the demand of energy. There is a clear increasing trend in PEMFC stack cooling demand, which decreases to a point of approximately 2.1 kWh/day in January to more than 3.2 kWh/day in March, following the emergence of higher power consumption and higher heat removal needs by the ambient conditions. Similarly, fuel processing increases with the operational intensity, in that, the processing of fuel rises by a factor of almost three in January (approximately 2.3 kWh/day) to almost three times that in March (almost 3.0 kWh/day). By contrast, battery management shows relatively stable consumption (1.72 to 2.0 kWh/day), which had a slight peak in February, as the load swings became increasingly pronounced.

The solar integration is highly seasonal with the peak reaching about 1.2 kWh/day in January and gradually rising to 2.0 kWh/day in March indicating the rising contribution of renewable resources as solar availability increases. Auxiliary loads are comparatively low and constant (~1.1 -1.4 kWh/ day), although their contribution is crucial in maintaining navigation, safety and control systems. Interestingly, the growth pattern of thermal recovery shows steady increase as the value of thermal recovery reaches up to 2.2 kWh/day in March, which indicates the efficient utilization of the wasted heat to support other second-order processes and enhance the efficiency of the system. Combined, these findings offer important information on the multidomain behavior of the hybrid system.

The prevalence of cooling and fuel processing underline the difficulties in running the PEMFC-based propulsion, and the gradual increase of solar integration and thermal recovery underlines the importance of renewable supplementation and the use of the waste-heat in the increase of the sustainability. The seasonal, environmental and load-dependent changes in priorities in the subsystems, as explained by the month-to-month variability in the bar chart also explain the necessity of adaptive energy management techniques that can modify the priorities of the subsystems depending on the season, environment, and load requirements.

Figure. 12 shows how the hydrogen fuel energy is divided into a PEMFC-battery hybrid system as a function of current density setpoints (j = 0.4, 0.6, 0.8, and 1.0 A cm^{-2}). The results illustrate how the ratio between useful power generation and inherent loss mechanisms varies with increasing electrochemical load. Every bar shows the total fuel energy divided by 100 % of the lower heating value (LHV) of hydrogen and subdivided into useful electrical output, activation losses, ohmic losses, mass-transport losses, auxiliary loads and recoverable thermal energy.

The system reaches its maximum electrical efficiency of around 55 at the lowest current density of 0.4 A cm^{-2} and over half of the hydrogen LHV is directly transformed into useful power. The losses are relatively moderate: activation losses are about 12, ohmic resistance is about 10 and mass-transport limitations are negligible at 6. Auxiliary loads eat up approximately 8 % of the fuel energy, and approximately 9 % is on tap as recoverable thermal energy. This highlights the advantages of operating at low to moderate current densities in

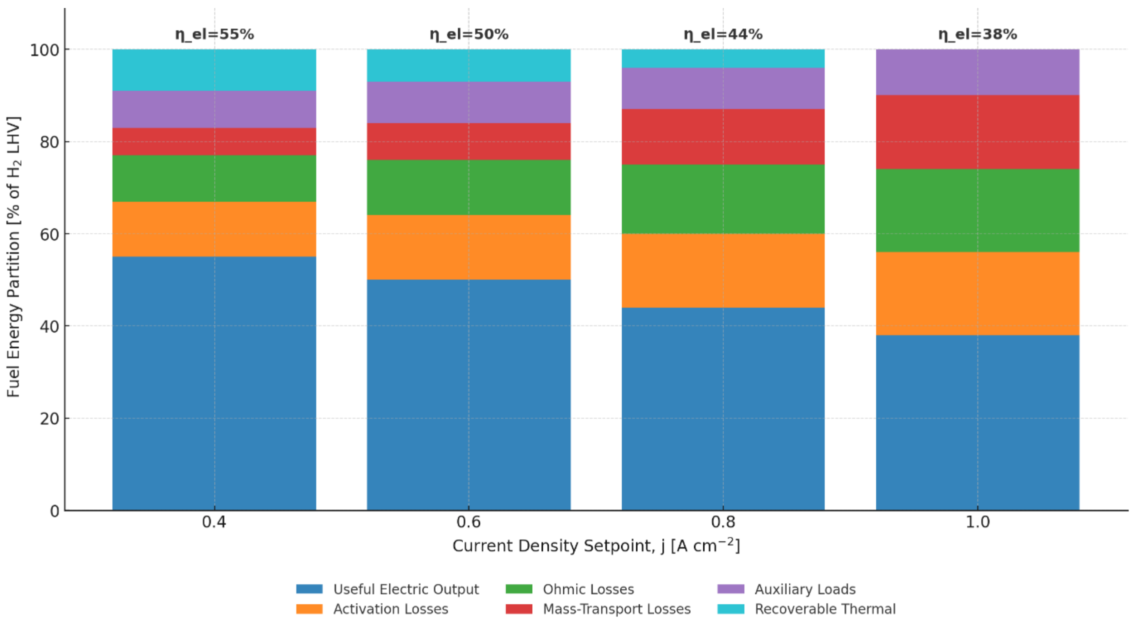

Fig. 12 Energy partitioning of the hybrid PEMFC–battery system at different current densities, showing useful electrical output, electrochemical losses, auxiliary loads, and recoverable thermal energy, illustrating efficiency degradation at high operating loads.

the operation of the fuel cells, where losses are kept minimal and efficiency is maximized.

The electrical efficiency decreases to 50 % as the current density grows to 0.6 A cm^{-2}. The useful power fraction goes down, and activation and ohmic losses increase (14% and 12%, respectively). The mass- transport losses are also increasing to approximately 8, which indicates the occurrence of diffusional limitations. The share of recoverable thermal energy goes down to 7 %, indicating the transfer of input power to recoverable heat and irreversible losses.

At higher frequencies of 0.8 A cm^{-2} the efficiency reduces to 44 %, and the resistance and transport losses become very large. Ohmic losses increase to about 15 % and mass-transport constraints grow to about 12 %, which confirms that increased load demand drives the system to a regime where polarization of concentrations dominate. The effective portion of power to work is reduced significantly, and the auxiliary requirements (9%) also stay the same. Recoverable thermal energy is reduced to about 4% with less possibilities of waste-heat recovery.

Lastly, at 1.0 A cm^{-2}, electrical efficiency drops to 38 %, which is the point of strongly loss-dominated operation. Activation and ohmic losses contribute about a third of the total energy and mass-transport constraints increase to ~16 %. The fraction of the auxiliary load increases marginally to about 10 % and the fraction recoverable of the thermal drops to zero and secondary energy harvesting is no longer possible. Such a regime cannot be sustained indefinitely because it puts heavy demands on the PEMFC stack and other subsystems.

Figure 13 illustrates the availability analysis of the hybrid PEMFC–battery propulsion system in the context of 14-day working period, and the subsystem conditions were divided into Online, Maintenance, and Offline. The findings are displayed in a two-panel chart, with the left panel measuring the percentage break down of the operational states over the period of the study, and the right-hand panel providing a daily timeline for each subsystem. Combined visualization does not only focus on the overall reliability of the system in terms of performance but also the individual subsystems, which pose vulnerabilities or increased maintenance requirements. The PEMFC stack had a balanced profile with online availability of 57 % with 21 % maintenance and 21 % offline. This implies that, though the stack can be used most of the time, it experiences considerable maintenance requirements and downtime, so it is both sensitive to thermal load and conditions in the fuel supply. Conversely the battery bank exhibited far greater stability, having 86 % online time, and zero offline incidents, although it also needed to be maintained (~14) to ensure charge discharge efficiency and eliminate degradation. The cooling subsystem demonstrated the highest reliability, being 100 % online during the whole period of observation and it validates its well-engineered design and importance in the thermal stability of the stack.

Other support subsystems, such as air supply and hydrogen supply, exhibit different behavior. The availability of air supply was high (93 %), and the compressor and blower parts were robust (7 %) as there were few maintenance requirements. The hydrogen supply line had an online availability of 79% and a maintenance and offline of 14 and 7 %respectively indicating that hydrogen storage and distribution experience periodic disturbances, potentially caused by pressure control or purity. Equally, thermal recovery was very dependable with 86 % online capacity with only a few instances of maintenance (14 %), ensuring that it is involved in uninterrupted energy recycling with no critical failures. Intermediate availability patterns were shown by the inverter and control system. The inverter had a 71% online availability with 21% maintenance and 7% offline indicating the need for frequent inspection of power electronics under variable load conditions. The control system which is used to coordinate the systems had an online availability of 79% with relatively high maintenance requirements (~21%), indicating both the complexity of its operations and the necessity of software-hardware calibration to prevent shutdowns.

The timeline panel highlights also the trends of the subsystem reliability through visualizing the daily states. The intermittency of the offline clusters in the PEMFC stack is usually high, with higher concentration in the mid-operation days, which happen to be the period on which there is high demand. The cooling system and battery bank are kept in the dominance of green (online) blocks, which highlights their stability. The supply of hydrogen and inverter subsystems show alternating green and orange patterns, which means that they have short but frequent maintenance periods instead of long-time outages. This is unlike the PEMFC stack where the red blocks emphasize even more serious outages.

Fig. 13 Availability analysis of the hybrid PEMFC–battery system over a 14-day operation period, showing percentage distribution of Online, Maintenance, and Offline states (left) and daily subsystem status timeline (right), highlighting system reliability and maintenance patterns.

The findings underscore thatthe hybrid PEMFC-battery design offers a very flexible and robust platform of maritime propulsion, which can strike a balance between efficiency, safety and availability with varying operating conditions. The performance measurements revealed that the electrical efficiency decreases nonlinearly with the current density, which decreases to almost 55 %at 0.4 A cm^{-2} down to 38 % at 1.0 A cm^{-2}, although hybrid load management can prevent such efficiency losses by concentrating peak demand on the battery and using recoverable thermal energy. The multi-axis performance plots and subsystem usages charts further highlighted the critical importance of cooling, fuel processing, and renewable integration and how the system can remain stable whilst changing to meet the fluctuating requirements. Lastly, the available analysis indicated that despite the intermittent downtime and high maintenance requirement of the PEMFC stack, the battery bank, cooling subsystem, and thermal recovery unit ensure system stability through high availability and minimal downtime. Such results demonstrate the significance of predictive maintenance, optimal current density operation, and unified energy management in improving the reliability of the system in the long-term. Finally, the overall findings prove that a hybrid system of PEMFC-battery not only is technically feasible to propel a marine ship but provides a long-term solution to decarbonize maritime activities and guarantee operational safety and efficiency.

To situate more the results obtained, a comparison is made with the current research done on hybrid PEMFC battery marine propulsion systems. The efficiency increase in this study (as high as 52.6 %) aligns with the results of (Zhang *et al.*, 2026; Zhang *et al.*, 2023), who found efficiency increases in the range of 45–50%when using rule-based energy management strategies. On the same note, Wang *et al.* (2022) also indicated that under a dynamic load condition, hydrogen consumption is greatly reduced by hybridization, which is consistent with the reduction in fuel consumption in this study. Nevertheless, enhanced stability of systems and thermal management is observed because of the adoption of advanced control methods such as model predictive control (MPC) and eco-cooling designs in the current study. The proposed system has a higher load-following capability and lower rates of battery degradation than conventional methods that have been reported in the literature. These results indicate that integrated control and thermal management are effective in improving overall performance and reliability of hybrid marine energy systems.

4. Conclusion

This work provides an in-depth analysis and optimization of a hybrid PEMFC–battery propulsion system in a marine environment under dynamic working conditions. The findings indicate that the suggested hybrid design has a great potential to improve the performance of the system in comparison with a traditional PEMFC-only baseline system attaining the efficiency increase of up to 52.6% and a significant decrease in the amount of hydrogen consumed. The battery support also increased load-following and minimized the pressure on the fuel cell stack, which helped to achieve improved durability and operational stability.

Additionally, the use of advanced control strategies such as model predictive control (MPC) and eco-cooling designs allowed to achieve good thermal control and enhanced safety margins through improved control of operating conditions. The system was also found to have better energy distribution and reduced auxiliary losses which support the applicability of the system in real world marine applications.

Altogether, the results support that the hybrid PEMFC–battery systems, combined with effective control and thermal management strategies, can provide a promising and efficient solution in the sphere of a decarbonated and sustainable maritime propulsion.

List of Symbol

Symbol	Description
Pload(t)	Propulsion load demand at time tt
PPEMFC(t)	Power supplied by PEMFC stack
$P_{Batt}(t)$	Power supplied/absorbed by battery
η_{PEMFC}	Efficiency of the PEMFC stack
V_{cell}	Actual operating voltage of a PEMFC cell
ENernst	Reversible voltage from Nernst equation
η_{act},η_{ohm},η_{conc}	Activation, ohmic, and concentration losses
$mH_2(t)$	Hydrogen mass flow rate
$I_{stack}(t)$	Current drawn from PEMFC stack
N_{cell}	Number of PEMFC cells in the stack
MH_2	Molar mass of hydrogen
F	Faraday's constant
J	Overall optimization cost function
α,β,γ,δ	Weighting coefficients for objectives
$R_{safety}(t)$	Safety risk penalty
$C_{deg}(t)$	Battery degradation cost function
DoD	Depth of discharge
$I_{Batt}(t)$	Battery current
SOC	State of charge
TPEMFC	Stack temperature
K_p,K_i	Proportional–integral gains for control
$LHVH_2$	Lower heating value of hydrogen

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