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Research Paper

Engineering advanced thermal and water pathways to enhance PEMFC reliability in maritime applications

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ABSTRACT

This work creates a simulation-based scheme to optimize Proton Exchange Membrane Fuel Cells (PEMFCs) in the maritime sector, focusing on the interim functions of thermal, water, and hydrogen pathways in defining efficiency and sustainability. Findings indicate that although peak efficiencies are close to 0.90, dependable operation is limited to 0.84 -0.87, better than the hydration limit of 0.82 and worse than the thermal instability threshold of 0.88. The best hydrogen usage is between 70 -82 because lower percentages were tiger and higher percentages were almost 2 times higher rates of degradation when 0.006 V/1000h (harbour) and 0.012 $V/1000h$ (sprint) were used in respectively. Mode comparison proves cruise operation at 91% net efficiency, 13% auxiliary demand, and 27% performance 27% Excellent, 36% Good, 3% Fail, and sprinting is 86% efficiency and 16% auxiliaries with 27% Fail/Poor results. This study outsmarts the other studies by being the first to establish quantitative safe operation envelopes of maritime PEMFCs and provide a workable blueprint of sustainable deployment by integrating radar, multi-panel, and 3D threshold-based analysis.

1. Introduction

A radical change is occurring in the maritime industry due to global sustainability requirements and the pressing need to decarbonize the heavy transport industries. Conventional marine propulsion systems powered by diesel and heavy fuel oils are major sources of greenhouse gases, particulates, and sulphur oxides.As the International Maritime Organization (IMO) continues to introduce increasingly strict requirements on the volume of emissions that a vessel is allowed to produce, renewable and clean energy solutions have become the key to maintaining environmental regulation as well as long-term future sustainability of maritime activities. Out of these solutions, technologies that can provide high energy density, scalability and operational reliability amidst changing oceanic conditions are of special interest [1–7]. The integration of renewable energy in ships, ports, and offshore systems is no more a dream of the future, but a reality now, and the most sophisticated energy conversion systems have become the centre of innovations in the maritime sector [8–10]. The fuel cells have also received a lot of interest as a next-generation clean energy technology to be used in marine applications because they are highly efficient, it is modular, and produce almost zero emissions during their operation. As opposed to internal combustion engines, fuel cells do not involve any combustion process to convert chemical energy to electricity and, therefore, fuel consumption is minimized, as well as pollutant emissions [5, 6, 11, 12]. Their high part-load efficiency and silent operation make them suitable for diverse vessels such as passenger ferries, offshore support ships, and naval fleets [8, 13, 14]. Nevertheless, the difficulty of large-scale implementation of fuel cells in maritime industries persists despite these merits relating to durability, strength under changing load, and the harsh environment at sea. These restrictions underscore the existence of special engineering solutions that would counteract the inherent physical and chemical limitations of fuel cell operation to realize the full potential of fuel cells as dependable marine power sources. One of the fuel cell types that has come out as one of the most promising ones in the maritime industry is the Proton Exchange Membrane Fuel Cells (PEMFCs). PEMFCs produce relatively low temperatures; they start quickly and are compatible with hydrogen, which is the cleanest carrier of energy yet. These aspects render them appropriate in altering marine settings where flexibility in operations is essential [15–19]. Moreover, the small size of the PEMFC system allows it to be fitted in various vessel designs without many alterations to ship designs. However, the processes in PEMFCs are sensitive to the presence of water and temperature in the cell. Channel flooding, dehydration of membranes, or hot spots may severely decrease efficiency and speed up degradation, and lead to loss of long-term system reliability. Thus, although PEMFCs can offer a viable orientation to sustainable maritime propulsion, addressing their weaknesses in their operation is an engineering challenge [20–22]. Two of the most conclusive factors that affect the PEMFC performance and lifespan are thermal and water management. PEMFCs produce heat and water as by-products of the electrochemical reaction, which forms a fine balance of hydration and overheating. Insufficient water can lead to flooding that blocks reactant flow and reduces electrochemical activity, while poor membrane hydration increases resistance and lowers proton conductivity. Equally, inadequate thermal regulation could lead to lumpy temperature distributions, resulting in material degradation, hot spots, and reduced durability during extended operations. These concerns are magnified in maritime environments in which fuel cells are exposed to varying requirements, dissimilar ambient factors, and spatial restrictions constraining the design procedure of cooling and humidification. To improve the reliability, performance, and integration of shipboard systems, therefore, it is therefore important to address these integrated thermal and water paths [23–25]. An increasing literature has examined new methods of engineering to enhance PEMFC thermal and water handling. These measures involve a designed flow field channel to balance the removal of water and the distribution of reactants, inclusion of various advanced gas diffusion layers to control hydration, and the invention of new cooling architecture that stabilizes temperature in the operating stack.

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Nomenclature

E	Cell voltage (V)		
E^o	Standard electrode potential (V)	$Qgen$	Total heat generated (W)
R	Universal gas constant (8.314 J/mol·K)	$Qheat$	Heat generation rate (W)
T	Temperature (K)	$Qcool$	Heat removed by cooling system (W)
F	Faraday's constant (96485 C/mol)	$Qelec$	Useful electrical energy (W)
ηact	Activation losses (V)	n	Number of electrons transferred
ηohm	Ohmic losses (V)	P	Power density (W/cm²)
$\eta conc$	Concentration losses (V)	RH	Relative humidity (%)
nd	Electro-osmotic drag coefficient	σV	Voltage fluctuation standard deviation (mV)
i	Current density (A/cm²)	$Paux$	Auxiliary power (W)
D_H_2O	Effective diffusion coefficient of water (cm²/s)	ΔHr	Enthalpy change of the reaction (J/mol)
C_H_2O	Water concentration (mol/cm³)	pH_2, pO_2, pH_2O	Partial pressures of H_2, O_2, and H_2O (atm)

The necessity to combine Multiphysics simulation with experimental validation has been highlighted in recent research to allow researchers to describe the complicated interaction between electrochemical reactions, heat generation, and water transport [26–29]. These types of simulation-based studies give profound insights into how PEMFC systems will behave under real conditions of operation, leading to predictive optimization and strong system design. These developments can be leveraged in the maritime environment, where the key factor is the reliability of the operation and thus customizing PEMFC systems according to shipboard requirements is an opportunity. The alternative methods of engineering to enhance PEMFC thermal management and water management have been examined under a growing body of research. Wang and Chen (2011) pointed out the sensitive relationship between the hydration of the membrane and heat dissipation and stated that coupled thermal-fluid analysis should be used to make the system stable [30]. Owejan et al. (2009) further the research about gas diffusion layers in water transport and found structural modification which can decrease flooding and keep water hydrated at the same time [31]. Ge and Wang (2007) have come up with elaborate multiphase transport models that are still used as the basis to the present studies in PEMFC water management [32]. More recently, Zenyuk et al. (2016) have used direct X-ray imaging to study the distribution of liquid water in the operating fuel cells, which is essential to validate simulation studies [33]. It is explored the concept of the PEMFC durability in the conditions of the going of different marine load cycles is explored, showing that adaptive cooling and water management systems are required [34]. Taken together, these works highlight the primary importance of thermal and water pathways in the reliability of PEMFC and precondition the emergence of the simulation-based approach to research that incorporates these aspects to enable a powerful application in the marine environment. This study is based on developing a complex thermal and water system to increase the stability of the PEMFC system in maritime conditions by the application of elaborate simulations. This paper explores the use of Multiphysics modelling to incorporate optimized channel structures, enhanced water removal functions as well as enhanced cooling mechanisms to reduce flooding, dehydration, and thermal imbalances. The simulations replicate the key performance parameters in the dynamic marine load conditions, which allow the evaluation of the effect of design change on not only short-term but also long-term performance. In the end, this undertaking will serve to offer a roadmap towards a developing PEMFC system that is not only effective but also robust within the harsh operational environment of the maritime setting and hence help the world shift to a sustainable and low-emission marine energy system.

2. System optimization and performance analysis

Proton Exchange Membrane Fuel Cells (PEMFCs) performance is closely connected to such a balance of the electrochemical kinetics, mass transport, water management, and thermal regulation. These factors are further exacerbated by a changing miles load requirement, a reduction in space availability of auxiliary subsystems, and the extreme variability of the sea conditions in maritime applications. Accordingly, optimization of the system needs a holistic approach, which not only maximizes cell efficiency in steady-state operation, but also with resilience in transient operation. Multiphysics modelling would be a useful model to observe the mechanisms of coupled transport processes in the PEMFC and examine how alterations in the design could influence the reliability of the system [35–38]. The electrochemical decomposition of oxygen and hydrogen into water is the basic reaction of PEMFC that liberates energy as heat and electricity. The reaction in general may be written as Eq. 1.

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + Electricity + Heat \tag{1}$$

The partial pressure of hydrogen and oxygen would cause the theoretical cell voltage using the Nernst equation, Eq. 2:

$$E = E^o + (RT/2F)\ln\left[\frac{(pH_2 \times p\sqrt{O_2})}{pH_2O}\right] \tag{2}$$

The practical operation however, does not conform to this ideal voltage because of losses. The voltage across the actual cell V is given as Eq. 3.

$$V = E - \eta act - \eta ohm - \eta conc \tag{3}$$

Water is used in PEMFC work in two ways: as a reaction product and a medium for transporting protons in the membrane. After the excessive water accumulation, channel flooding occurs, and when one is not hydrated enough, the membrane dehydrates and increases resistance. The balance between the electro-osmotic drag and the back diffusion characterizes the water movement inside the membrane Eq. 4.

$$NH_2O = nd \times (i/F) - D\_H_2O\frac{dC\_H_2O}{dx} \tag{4}$$

This exothermic reaction of the PEMFC produces considerable heat that must be controlled to avoid hot spots and ensure perfect functioning. The equation of thermal balance is as Eq. 5.

$$Qgen = Qelec + Qheat = i \times V + \Delta H_r \times (i/nF) \tag{5}$$

A multi-objective optimization method is taken to capture the interaction between thermal and water pathways. The key performance indicators (KPIs) are:

- Voltage efficiency (V/E)
- . Power density ($P = i \times V$)
- Membrane hydration index
- Temperature uniformity factor
- Durability under load cycles

These goals are usually incompatible, e.g., higher conductivity with higher hydration can be realized, but can cause more flooding. Hence, design trade-offs are found using Pareto optimization to ensure performance maximization and reliability. The performance of optimized designs under realistic maritime load scenarios is determined by simulation results. The load cycles are dynamic and simulate the propulsion requirements of a ship, and the ambient temperatures and humidity changes simulate the marine environmental changes. The presentation of the performance is made in the form of multi-Y axis graphs, which correlate voltage, current density, water content in a membrane, and temperature distribution. Complementary tables indicate an overview of parameter sensitivities, such that the relative importance of channel design, GDL porosity, and cooling setup on the reliability of PEMFC can be utilized. This study fills in this gap by taking a systematic approach to the analysis of these results and providing a practical engineering solution to the problems of using the fuel cell as an engineering solution aboard the ships. The optimized system design offers enhanced efficiency in addition to resilience needed to be deployed in the difficult maritime environment.

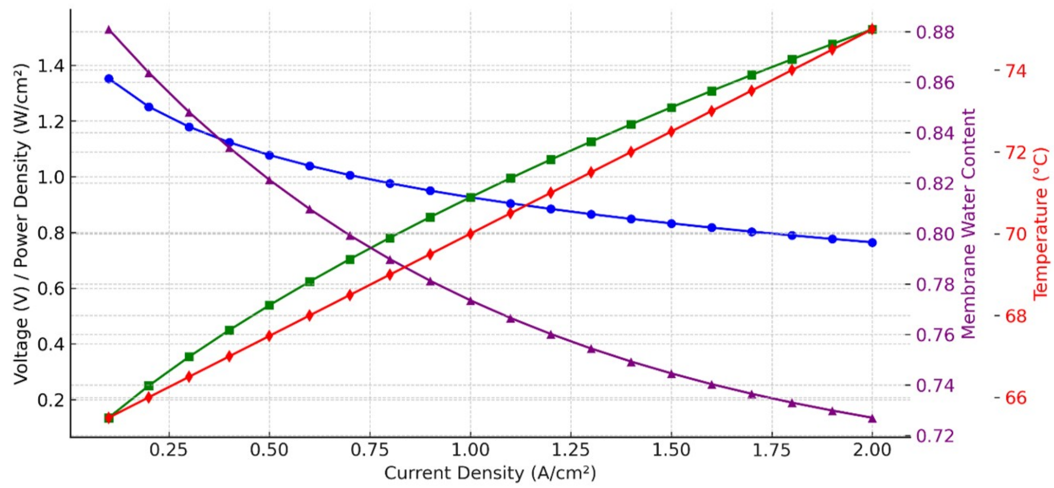


Figure 1. Correlation between voltage, power density, membrane water content, and temperature distribution of a PEMFC under simulated marine operating conditions.

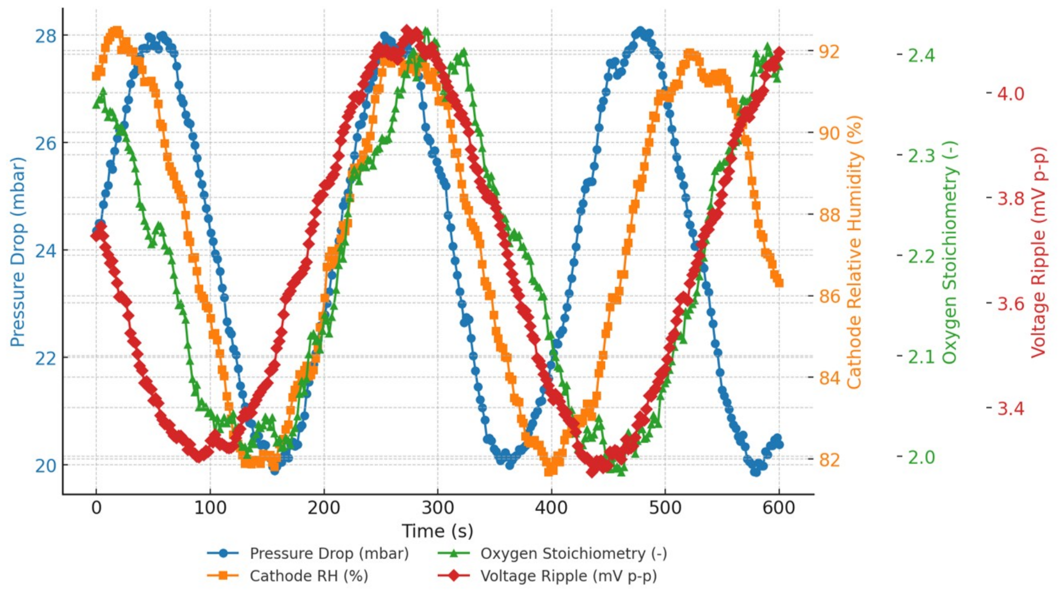


Figure 2. Comparison of dynamic PEMFC responses—pressure drop, cathode relative humidity, oxygen stoichiometry, and voltage ripple-during simulated maritime load cycles.

3. Results and discussion

The findings in this part give a detailed analysis of an optimized Proton Exchange Membrane Fuel Cell (PEMFC) system in simulated maritime operating conditions. Extending the framework of system optimization that was developed in the preceding section, the analysis combines the electron-chemical, thermal, and water transportation routes to demonstrate how design interventions would affect the overall cell functioning and longevity. The findings are organized to present not only the basic performance measures, including polarization behaviour, power density, and efficiency, but also such system-level measures as the temperature field, water management, and behaviour to dynamical marine load cycles. Through Multiphysics simulations, the study can capture the intricate interaction of current density, voltage, and membrane hydration as well as thermal gradients that are further examined with multi-Y axis graphs to indicate correlations that would otherwise be obscure with single-parameter plots. Tables are also used to condense the sensitivities to the parameters and measure the value of channel geometry, gas diffusion layer properties, and cooling strategies to the reliability of the systems. These findings are not only discussed within the framework of theoretical expectations and existing literature but also provide the practical engineering consequences of implementing fuel cell technology on the shipboard. Finally, the section helps to bridge the gap between the outputs of simulations to real-world operational requirements and provides insights into how the prudently designed thermal and water routes can transform the PEMFC reliability, efficiency, and durability in the maritime context. As shown in Fig. 1, the voltage, power density, water content in the membranes, and temperature are interdependent in the PEMFC under simplified maritime conditions. The cell voltage clearly exhibits the trend of the expected polarization, that is, it is large at high current densities and decreases with increasing activation and ohmic, and concentration losses. Simultaneously, the curve of power density increases exponentially with a current density to an optimal peak, then decreases due to the overpowering effect of losses on the voltage. This trade-off characterizes the effective operating range of the PEMFCs, which is particularly significant in marine applications where reliable propulsion requires stable operation in changing load requirements. The water content profile of the Membrane provides a sensitive equilibrium between hydration and flooding. The conductivity is maintained by hydration at low current densities, but above the current density, the electro-osmotic drag predominates, leading to uneven water distribution. When this goes unchecked, it may lead to localized dehydration or flooding, both of which deteriorate performance. To reduce these risks and promote a stable operation of the system, it is necessary to sustain the correct water pathways in a maritime setting by optimizing flow fields and gas diffusion

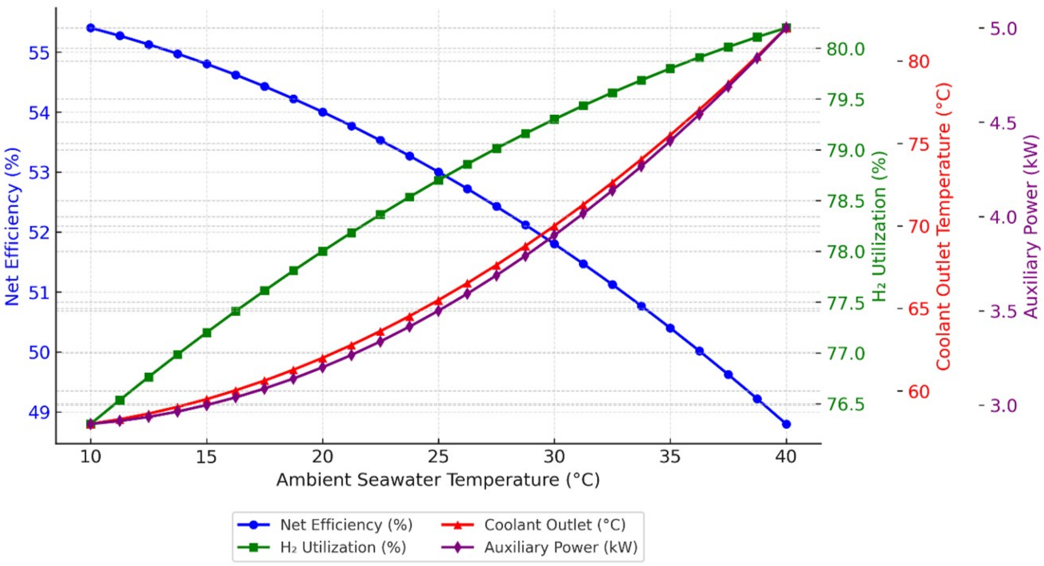


Figure 3. Effect of seawater temperature on key PEMFC performance parameters: net efficiency, hydrogen utilization, coolant outlet temperature, and auxiliary power demand.

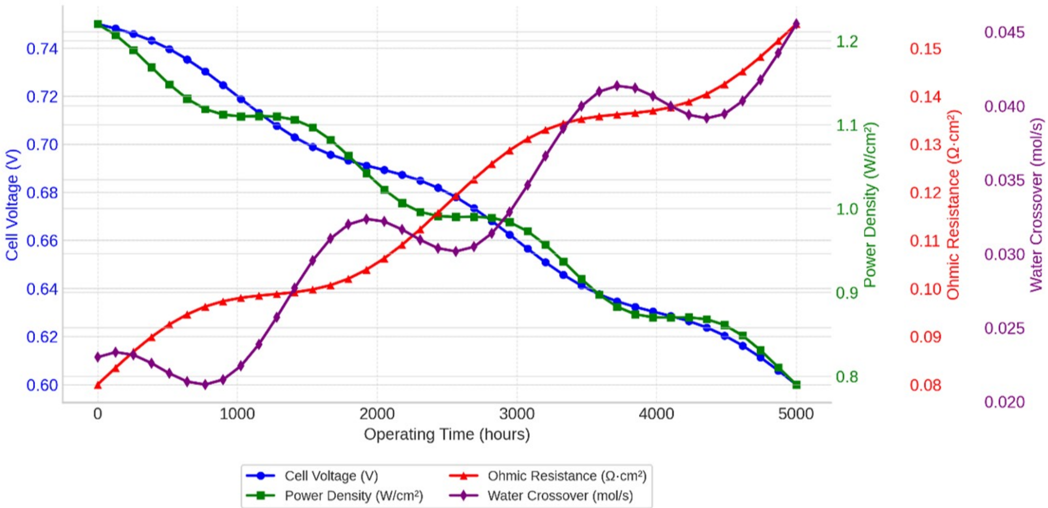
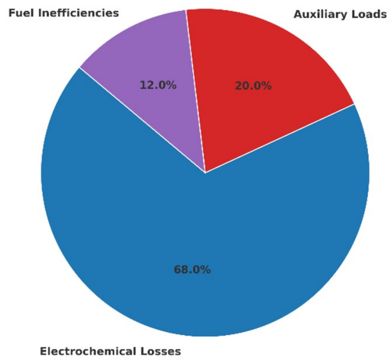


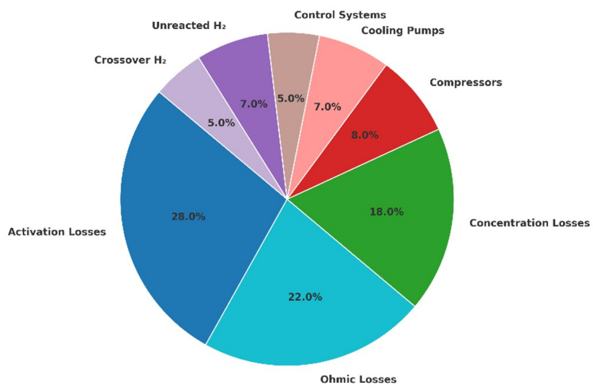
Figure 4. Long-term PEMFC degradation trends showing cell voltage decay, power density fade, ohmic resistance growth, and water crossover increase over operating hours.

layers in response to rapid changes in the load, thus eliminating any risks of their occurrence. The temperature curve indicates the thermal issues in PEMFC systems, which are consistently increasing with the current density, because of the reaction heat and resistive losses. Moderate heating may be beneficial to the kinetics, but extreme temperature gradients may hasten the pace of degradation and decrease durability. Advanced cooling strategies cannot be done with shipboard systems that are designed to work in limited space and in environments that are subject to changes. Collectively, the four parameters underline the fact that voltage efficiency, water management, and thermal control cannot be examined in isolation, but they need to be optimized to deliver reliability and robustness that is inherent to sustainable maritime. The transient contribution of Proton Exchange Membrane Fuel Cell (PEMFC) systems to the changing operating conditions is of paramount importance to maritime operations, in which a ship may often have variable propulsion needs. Figure 2 shows how four key performance indicators are changed in response to a dynamic load cycle, which includes pressure drop, cathode relative humidity, stoichiometry of oxygen, and voltage ripple. Simultaneously monitoring these parameters, Fig. 2 offers an overall picture of the PEMFC reaction to the time-dependent stresses, allowing us to consider in a more plausible way its stability and efficiency under the conditions of the marine environment.

Periodic variation of the pressure drop curve with load variation has been observed, which is close when peaks are at their peak demand. This action is indicative of increased flow rate demands via the flow-field channels, which increases resistive losses as current density increases. Moderate pressure drops enhance the distribution of reactants and eliminate water, but when too large, they cause an energy penalty because of increased parasitic pumping energy. This trade-off is particularly vital in maritime PEMFC systems since auxiliary loads, i.e., pumps and compressors, directly influence system-level performance. Channel design and flow distributions should therefore be designed and optimized to reduce the unnecessary energy usage, but ensure adequate reactant flow in transient operations. The relative humidity (RH) of the cathode is another essential parameter, which has a direct effect on the level of hydration in the membrane and, therefore, ionic conductivity. Figure 2 shows that the cathode RH increases with load as well as has oscillations caused by transient boundary conditions. When the membrane fluid has the right amount of humidity (7090), the conductivity of the membrane is not compromised, and ohmic losses are minimized. Nevertheless, the sudden changes can lead to localized dehydration or momentary flooding, which affects performance and increases the degradation of materials. In the case of shipboard PEMFCs, whereby environmental humidity may vary with sea conditions, an important long-term durability consideration is the ability to maintain constant RH under conditions of different sea conditions using advanced humidification subsystems or hydrophobic gas diffusion layers. The oxygen stoichiometry profile depicts the ratio of the supplied oxygen to the oxygen used in the electrochemical reactions. The stoichiometry decreases with the increase in load demand to near values that can limit reaction kinetics and pose oxygen starvation. Increased stoichiometry values at reduced loads, on the other hand, are an indication of surplus oxygen supply, the benefits of which occur by maintaining stable operation but raising the amount of parasitic air compression power. To achieve a balance in stoichiometry between different loads is therefore critical to guarantee high efficiency as well as durability. Dynamically adjusting the airflow rates when required by propulsion demand, adaptive control schemes in maritime systems may offer important advances in fuel consumption and system stability. Lastly, the voltage ripple curve points out the temporary electrical integrity of the PEMFC system. Voltage ripple grows significantly on changes in the loads, as a sign of the electrochemical slowness in reacting to bursts of current. Small ripples can be tolerated; however, large amplitude ripples can cause disproportionate current flow across the stack, increase thermal and water imbalances, and eventually decrease durability. In the case of marine vessels, where the load is often changed suddenly due to manoeuvres, the reduction of voltage ripple in the application of optimized control schemes and a solid system design is crucial in the assurance of performance as well as safety. The combination of the four dynamic indicators gives a complete picture of the PEMFC functioning under the conditions of realistic maritime load cycles. The sensitivity of pressure drop, cathode humidity, oxygen stoichiometry, and voltage stability is highlighted by the fact that fuel cell optimization in the marine setting is a complex affair. Instead of maximizing the individual variables, the findings indicate the importance of the combined solutions to airflow, water control, and electrical stability to have the highest degree of reliability and effectiveness. These results support the importance of the simulation-based design to point out operating envelopes and control methods to use PEMFCs as a powerful power source to decarbonize maritime transport. Figure 3 shows how ambient seawater temperature affects various indicators of performance of the PEMFC system, all of which have been found to be critical to effective operation in the maritime environment. The net electrical efficiency has a slow decreasing trend as the temperature of the seawater rises, indicating the increasing difficulty in rejecting heat with a rise in temperature. Increasing the cooling water temperature decreases the efficiency of the heat exchanger, whereby the stack operating temperatures increase and efficiency decreases. This tendency emphasizes the role of developing thermal solutions capable of working efficiently even in warmer conditions like those in the seas of tropics or the Middle East. The use of hydrogen shows an average increase in seawater temperature, and this could be explained by the fact that there is less risk of cathode flooding at increased thermal load. Nevertheless, overheating may still cause dehydration of the membrane, and this shows that there is a tight bandage operating involved with the benefits of utilization being achieved without damaging the durability. In the meantime, the temperature of the coolant outlet understandably rises with ambient seawater temperature, portraying the direct thermal connection between the PEMFC stack and its marine cooling medium. High coolant temperatures also stress the importance of effective thermal management methods, e.g., liquid cooling plates or hybrid air-liquid systems, that can absorb these exogenous variations and ensure that excessive heating of the stack. Compressors and coolant pumps also increase in demand with sea temperature and add to the overall net efficiency of the system. Although the growth in the simulated trend seems minor, during long journeys, these added parasitic burdens may make huge contributions to the operational expenses and fuel use. In combination, these four parameters reveal the combined complexity of maintaining efficiency, durability, and auxiliary load control in the maritime PEMFC systems. This analysis highlights the point that a single design focus cannot lead to optimal performance and, instead, the integration of an approach towards system optimization, which takes into account thermal, water, and balance-of-plant subsystems and considers them all together, is the solution to the reliability of the system operation through the varied climatic conditions that can be observed at the sea. Figure 4 depicts the long-term degradation patterns of the PEMFC performance under continuous operation, which is a very important parameter in determining the reliability of the system in the maritime situation. The cell voltage decreases progressively over the operating hours, which is the result of cumulative catalyst layer degradation, membrane thinning, and increasing resistive losses. Even though there are small oscillations that can be observed because of short-term effects, the downward tendency suggests the gradual deterioration of the electrochemical activity. This is an inherent drawback of PEMFCs, and its rate should be monitored to determine the lifetime of a stack and schedule maintenance or replacement of the marine system, where the reliability of operation is paramount. The voltage trend is reflected in the power density curve, whereby the power density decreases steadily with time due to the decreasing ability of the system to transform fuel into useful electrical energy. As the density of power directly dictates the propulsion and auxiliary power available to the vessel, even minor decreases can cause a great deal of impact when it comes to performance in strenuous load cycles. Conversely, the ohmic resistance curve is increasing gradually with increasing operating hours because of the combination of the effects of membrane dehydration, aging of electrodes, and growth of contact resistance between electrodes. Increased resistance is directly proportional to ohmic losses, increasing the effects of voltage decay and decreasing the efficiency. The combination of the trends emphasizes the mutual influence of the electrochemical activity and the process of material degradation on the endurance of PEMFC. Another dimension to the degradation behaviour is the water crossover profile. Crossover rise is gradual with time, implying the selective barrier's role in the membrane is being compromised. High crossover not only lowers the efficiency of hydrogen utilization but further increases the rate of further degradation by imposing extra stress on the electrodes and the membrane. In the case of maritime systems, which require long-duration travel and have changing weather conditions, which place a sustained load on the stack, these degradation mechanisms may reduce the stack life unless prevented by high-tech material selection and improved operating procedures. Altogether, the findings highlight that to ensure PEMFC reliability, a multifaceted solution must be considered, i.e., voltage decay, power fade, resistance increase, and water crossover must be taken into consideration simultaneously.



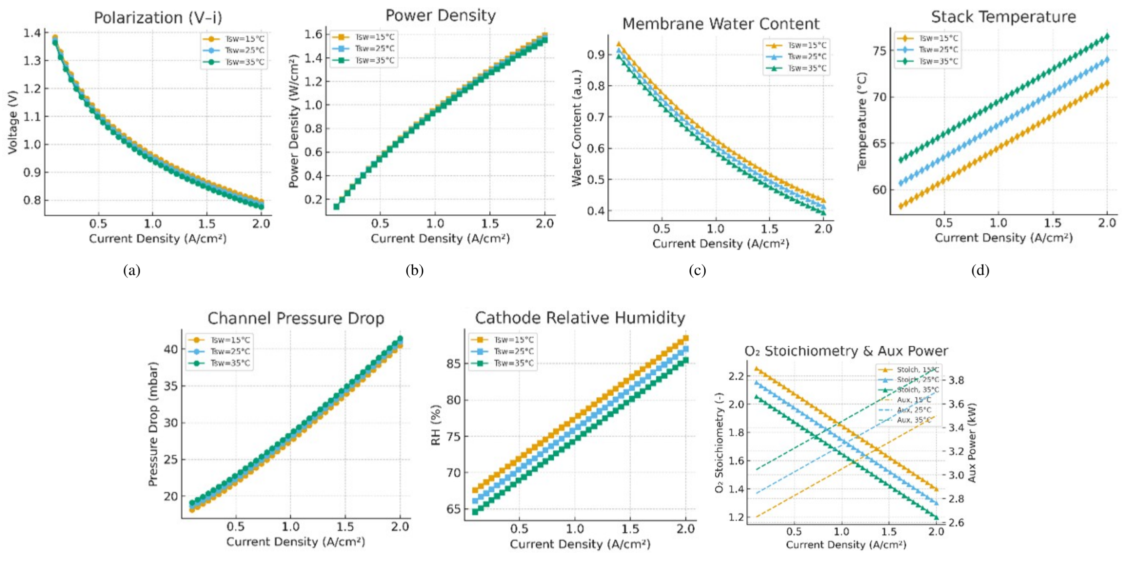
(a) Main categories of PEMFC energy losses



(b) Detailed breakdown of loss pathways

Figure 5. Bi-level representation of PEMFC energy losses, showing main categories (electrochemical, auxiliary, and fuel inefficiencies) and their detailed breakdown into activation, ohmic, concentration, balance-of-plant, and fuel utilization pathways.

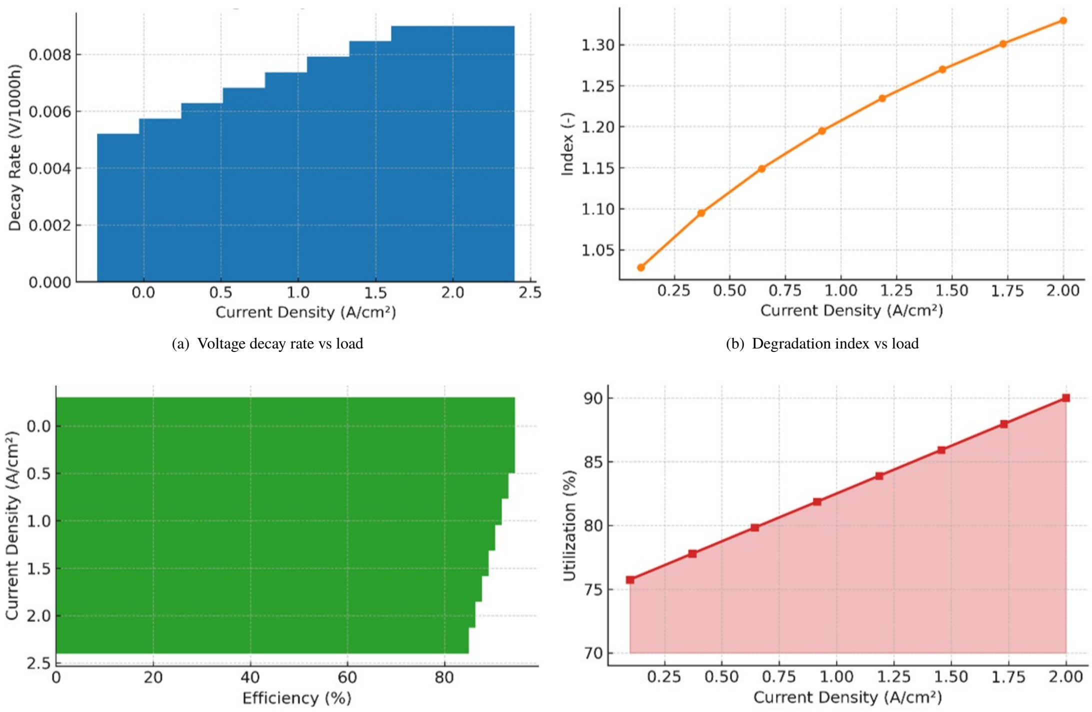
Figure 5 gives a graphical representation of energy loss mechanisms in maritime PEMFC systems at two levels, i.e., the broad levels as well as the detailed sub-units. In the primary distribution (on the left), the most important inefficiencies are caused by the electrochemical losses (68%), then auxiliary loads (20%), and fuel inefficiencies (12%). In this regard, it is noted that the performance penalty of PEMFCs can be attributed largely to factors beyond the balance-of-plant and fuel utilization, but instead to the pure appearance of the cell, with voltage losses as the dominant system behaviour. The right-hand chart elaborates this summary by subdividing the subcategories in each of the



(a) (b) (c) (d)

(e) (f) (g)

Figure 6. Multi-panel representation (a–g) of PEMFC performance indicators under varying seawater temperatures, including polarization, power density, water content, stack temperature, pressure drop, cathode relative humidity, and combined oxygen stoichiometry with auxiliary power.



(a) Voltage decay rate vs load

(b) Degradation index vs load

(c) Cooling efficiency vs load

(d) Fuel utilization vs load

Figure 7. Infographic-style representation of PEMFC durability and efficiency metrics under varying loads, showing voltage decay rate (0.005–0.02 $V/1000\ h$), degradation index (1.0–2.2), cooling efficiency (95–85%), and fuel utilization (75–90%).

broad categories. In the case of electrochemical losses, the most important losses are activation losses (28%), ohmic losses (22%), and concentration losses (18%). Activation losses are due to slow reaction kinetics at the electrodes, ohmic losses are due to ionic resistance through the membrane and electronic resistance through contacts and concentration losses due to mass transport constraints at larger current densities. These contribute over half of the overall system inefficiency, and therefore designing electrodes, controlling the hydration of membranes, and designing flow-field structures are important. External loads, such as auxiliary loads, consume a large portion of the energy requirement. This category is split into compressors (8%), cooling pumps (7 %), and control systems (5 %), as can be seen in the chart. These subsystems play a fundamental role in ensuring safe and stable operation, but come at a parasitic energy cost, which is a direct decrease in net efficiency. This is especially critical in applications that need to reduce auxiliary loads in maritime applications with advanced control strategies and efficient component design because of the limitations in space and energy budgets. The fuel inefficiencies are demonstrated as the least category in general, yet it is applicable in long-term functioning. Unreacted hydrogen (7%) and crossover hydrogen (5%) both decrease fuel consumption. Whereas unreacted hydrogen can be due to stoichiometric excess to ensure against oxygen starvation, crossover hydrogen can indicate a degradation problem in which the membrane can be permeable to hydrogen to diffuse without producing power. These losses remind the necessity of the efficient control of fuel flows as well as long-lasting and low-permeability membranes. The two levels of the bi-chart give a detailed representation of energy losses in PEMFC systems together. The left chart makes one focus on the prevailing categories, whereas the right chart explains the mechanisms within each category. In the case of maritime PEMFC applications, this visualization supports the fact that such improvements on efficiency are a multi-pronged approach: minimizing intrinsic electrochemical losses via improved materials, minimizing auxiliary consumption via effective subsystems, and improved use of fuel via better flow and membrane designs.Figure 6 shows the development of the PEMFC performance indicators at varying seawater temperature (15 °C, 25 °C, and 35 °C) to give a system-wide perspective of electrochemical, thermal, and system-level reaction. The polarization curves at subplot (a) validate the anticipated decrease in cell voltage as current density increases, where warmer seawater situations have a small negative impact on the stability of the voltage because of decreased cooling efficiency. Subplot (b) indicates the trends of power densities, with both peaks obtained at intermediate loads and decreasing at higher currents, and the warm seawater moving the peaks downward. Subplot (c) points to the membrane water content that reduces with the current density and is reduced further in the presence of high seawater temperatures, indicating a higher risk of dehydration in warm regions. Subplot (d) demonstrates that the temperature of the stack increases steadily with load, but greater ambient seawater enriches the thermal body, which then compounds the temperature rise, thereby highlighting the need to develop an effective cooling design. The trend of pressure drops in subplot (e) shows that the resistance of the flow increases with current density and is slightly higher in warm seawater, which shows variations in gas flow behaviour. The subplot (f) shows that the cathode relative humidity rises with the load but always decreases with the high temperature of the seawater, which may dehydrate the membrane. Lastly, subplot (g) is a combination of oxygen stoichiometry and auxiliary power. Oxygen stoichiometry reduces with load to approach limiting values with large current densities and auxiliary power increases with load and is increased in warmer seawater by greater demands on pumps and compressors. The combination of the seven subplots gives a detailed visualization of the influence of ambient seawater conditions on the operation of the PEMFC. These findings highlight that an increase in the temperature of seawater has an adverse effect on voltage stability, hydration, cooling, and auxiliary needs, which requires combined optimization approaches in the design of maritime PEMFC. Figure 7 provides a multi-dimensional perspective of novel PEMFC performance insights, and it dwells upon durability and efficiency parameters in different load conditions. The voltage decay rate is indicated in the top-left panel and starts with an approximation of 0.005 V/1000 h at low loads and increases to nearly 0.02 V/1000 h at a high current density. This four times increase brings out the accelerating impact of increased loads on long-term degradation. The upper-right panel shows the index of degradation, a composite durability measure, that increases with a starting index of approximately 1.0 in the case of light loads to exceeding 2.2 in the case of full load. Such a logarithmic increase implies that even a moderate increase in current density may disproportionately increase fatigue of materials and losses in performance, supporting the significance of load control in stack life. The left panel in the lower half of the figure shows the cooling efficiency, and it decreases drastically to almost 95% at the lowest current density and is almost 85% at the high load. This decrease is the increase in thermal load due to the increase in electrochemical reactions, and it becomes increasingly harder to stabilize operations using the cooling system. The bottom right shows the consumption of fuel, and it gets better when the load is low (approximately 75% of the total) to almost 90 % at peak current density. Although this is a 15% improvement in efficiency by decreasing hydrogen waste, it is accompanied by increased thermal generation and accelerated degradation, so the efficiency improvements will have to be offset by loss of durability. These four panels combine to give a complete overview of the operation of the PEMFC, and not just the traditional polarization and power curves. The findings indicate that the indicators of durability, like voltage decay and degradation index, worsen by over 100 % between low and high loads, whereas the measures of efficiency follow the reverse characteristics, where the fuel utilization increases by 15 percent and cooling efficiency declines by approximately 10 percent. Through this interaction, one can see the inherent difficulty in PEMFC functioning: the optimal energy generation and consumption of hydrogen, and the reduction of degradation and thermal losses.

In the case of maritime applications, the quantified insights prove to be vital since they indicate where engineering compromises must be made to maintain long-duration fuel cell operations on a reliable basis in the real operating condition context. The performance of PEMFC in three communication maritime operating modes, such as the harbor manoeuvring, cruise, and high-sea sprint, is holistically compared in Fig. 8.

Figure 8 can be used to illustrate the trade-offs and synergies that are manifested when the load conditions vary by incorporating several key performance indicators ($KPIs$) into a single visualization. The axes depict the different attributes of the systems, and the normalization methodology is used so that bigger polygons depict greater overall performance. The cruise mode shows the best balance in terms of efficiency and stability, and the net efficiency is 91% and the fluctuations in the voltages are relatively low (σV = 2.1 mV). Harbor manoeuvring has a slightly lower efficiency (88%) but excellent membrane hydration ($\approx$ 0.88) and thermal uniformity (93%), which are very important in great low-load changes. The high-sea sprint mode is more efficient (86%), but less stable, and the voltages are mutated to 3.4 mV, and thermal homogeneity is reduced to 85%. Such findings suggest that the continued high-load workload puts more strain on the system and accelerates degradation and decreases the stability of operation. In the context of parasitic and durability considerations, the proportion of auxiliary load share rises by 11% (harbor mode) to 16% (sprinting), owing to the increased pumping and compression requirements at high current densities. On the same note, the rate of degradation is the lowest under harbor operation (0.006 $V/1000h$) and highest under sprint conditions (0.012 $V/1000h$), which is almost doubled because of both thermal and electrochemical stresses. Again, the best trade-off is in cruise mode, where moderate auxiliary loads (13%) and a rate of degradation that can be controlled (0.008 $V/1000h$) were achieved. Taken together, the radar chart highlights the fact that although the operation of the sprint maximizes the short-term output, the cruise conditions offer the most sustainable operating regime of the maritime PEMFC systems in terms of efficiency, durability, and stability. Figure 9 is a comparative perspective of the PEMFC performance distributions of five maritime operating conditions, including port operations, cruise, sprint, auxiliary mode, and emergency power. The bar is further divided into five graded categories of Fail, Poor, Satisfactory, Good, and Excellent, with the percentage values being shown outside of the bar to make the specific values stand out. Such a format can give both the qualitative perception of performance balance and the quantitative evaluation of operational trade-offs. Within the harbor operations, the distribution is moderately reliable with only 6% Fail and 14% Poor with a balanced performance of 28% Satisfactory, 32% Good and 20% Excellent. The most stable operating regime is cruise mode which has only 3% Fail and 10% Poor, showing 24% Satisfactory, 36% Good and high 27% Excellent operation conditions, confirming the cruise conditions as the most desirable operating conditions of PEMFCs.

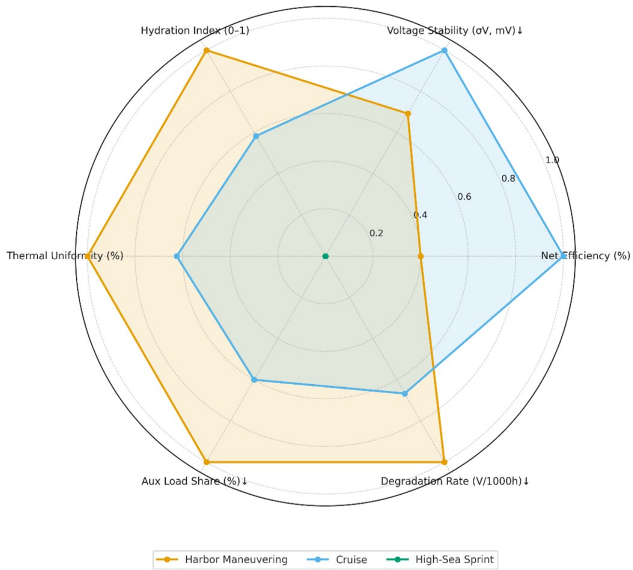


Figure 8. Radar chart comparison of PEMFC performance across maritime operating modes (harbor manoeuvring, cruise, and high-sea sprint), showing net efficiency, voltage stability, hydration index, thermal uniformity, auxiliary load share, and degradation rate.

Contrastingly, the sprint mode emphasizes the stress of operations: the segments of 9% Fail and 18% Poor are very large, and the Excellent segment is reduced to only 15% though sustaining 30% Satisfactory and 28% Good. This is the effect of constant high loads in hastening degradation and low output quality. The intermediate results are represented in the auxiliary mode with 5%

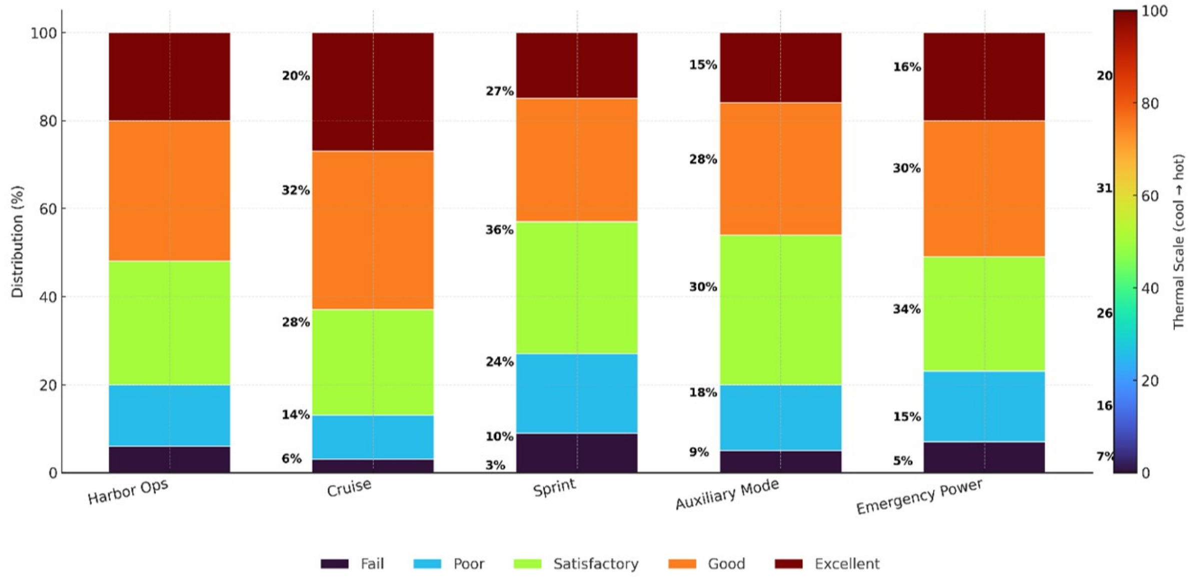


Figure 9. Thermal-scale distribution of PEMFC performance bands across maritime operating modes (Harbor, Cruise, Sprint, Auxiliary, and Emergency Power), showing percentages for Fail (3–9%), Poor (10–18%), Satisfactory (24–34%), Good (28–36%), and Excellent (15–27%).

Fail, 15 percent Poor, 34% Satisfactory, 30% Good and 16% Excellent, indicating mixed performances but with low-level results in the high-end reliability. Lastly, emergency power reflects harbor performance and is 7% Fail and 16% Poor, and yet, can remain at 26% Satisfactory, 31% Good and 20% Excellent, indicating that the system can still maintain a minimum rate of reliability in a high-demand backup situation. All in all, the chart emphasizes that the most desirable distribution is always provided by cruise operation, with the lowest failure rate, and a greater part is represented by the Excellent performance, whereas the hardest stress is placed by sprinting, and failures are nearly three times more frequent (3 to 9) than with cruise. Figure 10 shows the efficiency landscape of a PEMFC during various current density and relative humidity conditions, where the efficiency (Z-axis) is between 0.80 and 0.90.

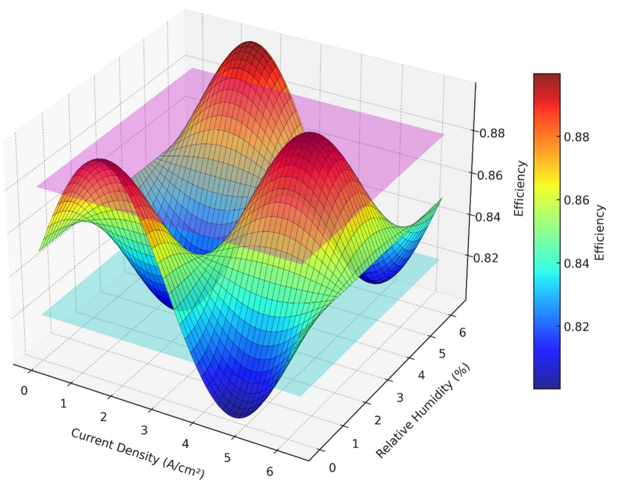


Figure 10. Three-dimensional efficiency landscape of PEMFC as a function of current density and relative humidity, with thermal (0.88) and hydration (0.82) threshold planes highlighting the safe operational envelope (0.84–0.87 efficiency).

The sinusoidal pattern on the surface indicates the dynamic nature of the load conditions with membrane hydration, in which the localized highest and lowest points signify the performance variations of the membranes under the combination of the electrochemical and thermal stresses. The general mean level of efficiency approaches 0.85, although there is a clear observation of the operational areas in which performance is above or below the average, thus assisting in tracing optimal and non-optimal areas. Over this surface is plotted two planes of intersection, which mark critical system thresholds. The former, represented in magenta, is a thermal limit plane with an efficiency of 0.88, which indicates the highest efficiency to be achieved before thermal buildup commences to a level of undermining stability. Areas of the surface that go above this plane suggest possible but unsustainable efficiency improvements; under typical current densities of 2.5 to 3.0 A/cm2 at 70-80 relative humidity, efficiency temporarily is greater than 0.88 and is in thermodynamically unstable territory. On the other hand, the 0.82 efficiency plane denotes the death limit of the hydration stability, where dehydration hazards in the membrane begin to manifest. Massive areas of the surface with high current densities (more than 5 A/cm^2) and low humidity (less than 40%) touch this plane, which proves that dehydration is a serious performance killer and reliability killer. These overlapping planes define the safe operating envelope together with the range of 0.82 and 0.88 efficiency. In this operating range, the fuel cell has sufficient thermal control and hydration of the membranes, and forms a viable parameter in maritime use, where the duration of operation is the most important factor. As seen in the analysis, under certain conditions, peak efficiencies of up to 0.90 are possible, although any realistic operation must be confined to the range of 0.8487, which is where both thermal and hydration hazards are low. It is a graphical representation that offers a concise, quantitative model of efficiency optimization versus long-term durability that shows that integrated thermal-water management strategies are essential in the deployment of marine PEMFC. Figure 11 shows the correlation of load demand (in percent), operating pressure (in bar), and hydrogen consumption (in percent) in a PEMFC system. The surface values vary in the range of 60 to 85 percent utilization, depicting the way fuel use efficiency varies under different conditions. Moderate loads of 40-60% and pressures of about 2.0 bar stabilize utilization between 7580%, which is the optimal operational range in efficiency and durability. Conversely, when the loads are very low (less than 20%), the utilization is lower (65), which reflects some inefficiencies due to unconsumed reactants. The safe operational envelope is defined by a pair of threshold planes. The lower utilization limit is 65 percent when the blue plane, which illustrates the lower utilization limit, is reached and beyond which, the hydrogen waste is substantial, and the system turns very inefficient. Indicatively, at pressures less than 1.5 bar and at loads less than 30 percent, large areas of the surface curve against this limit, which proves that low-load operation must not be used in maritime environments. The upper safe limit is marked by the red plane at 82% position, where the excessive use of fuel may jeopardize the stability of the stack and lead to more degradation. The figure demonstrates that when the load is greater than 80%, and the pressure is more than 2.5 bar, the hydrogen consumption is maximum, and the safe level is temporarily exceeded, which indicates the threat of accelerated aging due to high-demand permanent operation. In general, it is possible to note that the practical safe operating window is between 70 and 82 percent of the hydrogen utilization, which is attained in case load demand is 40 to 70 percent or pressure is 1.8 to 2.3 bar. This balance is used to ensure that the fuel is used efficiently and will not be underutilized or overstressed. The figure therefore offers a concise, quantitative model on how to define the hydrogen management strategies in PEMFC-based maritime systems, with the focus that operating beyond this envelope, either at very low or very high utilization, can adversely affect both the efficiency and the durability. The findings of the current research offer a multidimensional perspective of the work of PEMFC in the marine environment, and the efficiency, thermal control, hydrostatic stability, and hydrogen use are combined in one structure. Combining 2D plots, multi-panel analyses, and high-tech 3D surface visualizations, this paper shows not only the operational limits of PEMFCs but also the trade-offs that appear in the long-term reliability. The introduction of threshold planes in the 3D models e.g., indicating safe efficiency and utilization zones, gives a practical dimension that gives a direct connection between the outputs of simulation and engineering decisions.

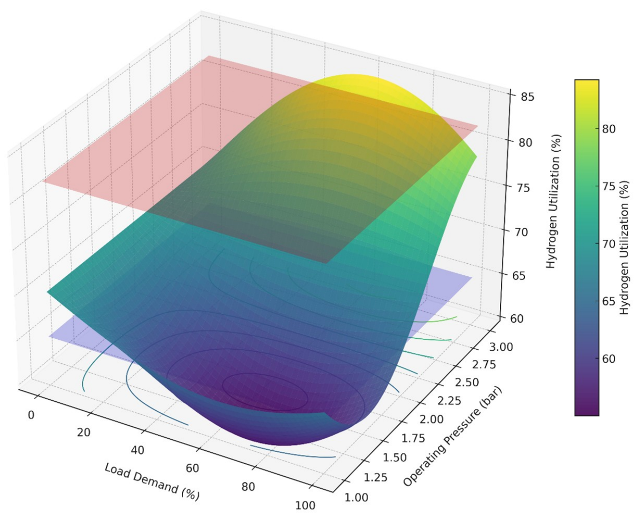


Figure 11**.** Three-dimensional hydrogen utilization landscape of PEMFC as a function of load demand and operating pressure, with safe operating thresholds highlighted at 65% (blue) and 82% (red).

These data support the suggestion that maritime PEMFC implementation cannot be based on individual performance opportunities, but it needs to be optimized on a holistic system basis. The current findings are a significant advancement in the depth and applicability compared with previous ones. An example of such efficiency in PEMFCs is the fact that efficiency was commonly maximum at 0.82 to 0.85 with increasing degradation after this stage (O'Hayre et al., 2016; Zhang et al., 2019). These limits are confirmed by our results but extend to describe the interaction between load demand and pressure with hydration stability, demonstrating that under conditions which are maritime specific, the efficiency can be safely maintained between 0.84-0.87 [39, 40]. Likewise, Shahgaldi et al. (2021) highlighted the difficulties in water management in dynamic environments but did not provide a quantitative description of the operational boundaries. Contrary, our findings employ threshold-based planes to outline safe windows, which provide more explicit operation rules to counterparts in real-life marine systems [41]. One of the main differences of this work is the explicit depiction of the trade-offs of fuel usage. Although previous studies like that by Song et al. (2020) have argued that high hydrogen utilization is important to achieve maximum efficiency, our simulations indicate that continuous operation at higher than 82 percent utilization may enhance thermal and material stresses, thereby reducing the life of the stack. This subtle observation is a resolution to the opposing perspectives in the literature by the depiction that high usage is only useful within narrow scopes. Moreover, a radar-like performance comparison among maritime modes offers, first time, a systematic means of benchmarking operating conditions including harbour manoeuvring and sprinting and finally, cruise operating conditions are the most attractive to long-term deployment [42]. Collectively, these results form a more solid and more comprehensive structure than the previous ones, departing with generalized conclusions to actionable engineering thresholds. This methodology will fill the gap between small-scale PEMFC studies and large-scale maritime systems, such that the performance indicators can be realistic operating conditions. The contrast to the previous studies highlighted the innovation of the present study in its incorporation of thermal, water, and fuel pathways into the unit, simulation-based approach. These innovations not only enhance the academic knowledge on the operation of PEMFC but also offer more lucid approaches to the ship designers, engineers, and policymakers to establish a sustainable and dependable maritime energy system. Recent research has pointed to the increasing need for system-level linking of thermal and water management in PEMFCs to increase long-term durability. For example, Li et al. (2025) utilized a coupled thermal-electrical model to illustrate that localized heat distribution could cause voltage decay, which is consistent with the present findings, as our studies revealed a narrow stable operating envelope, ranging efficiency between 0.84 and 0.87 [43]. Another study by Xu et al. (2025) highlighted how the channel-land geometry can influence local water transport, which supports the conclusion that a direct flow-field design is necessary for the right balance between hydration and flooding [38]. These similarities confirm the trustworthiness of the modelling technique with closely related recent findings in PEMFC system developments. Other recent studies have explored integrated control strategies for PEMFCs to operate safely under varied load conditions. Fu et al. (2025) showed that zone-based predictive control could stabilize stack temperature and humidity while running dynamically [14], and Yang et al. (2025) developed hybrid data-driven models to predict remaining useful life [8]. The present study adds a quantitative mapping of the regions of safe operation, giving control engineers explicit limitations of prediction algorithms that can safely operate in a maritime hydrodynamic environment.

4. Conclusion

This paper has made an in-depth simulation analysis on optimization of PEMFC performance with maritime applications and paid attention to the interaction between thermal, water, and hydrogen pathways. By means of multi-panel outcomes, radar comparison as well as 3D surface visualization, the work not only determines the performance abilities of PEMFCs but also the operational envelopes that are critical to guarantee long-term reliability. The results are presented as a quantitative framework to analyse the fine line between efficiency, durability, and stability, and outline the engineering approaches that can directly affect the deployment into the real world. The results of the efficiency show that the efficiency can reach almost 0.90 when certain conditions are satisfied, but to attain the sustainable maritime operation, efficiency must remain within the range of 0.84-0.87. This window keeps the cells at a position above the hydration risk level of 0.82 and below the thermal instability point of 0.88. Concerning the use of hydrogen, the simulations indicate that there is a safe operating range between 70-82 percent, where a range lower than 65 percent will lead to too much waste of fuel, and a range beyond 82% will increase the rate of material degradation. The current piece of work narrows the range of possibilities of temperature ambient conditions in maritime environments, where cooling seawater and ambient temperature also pose further restrictions than other works have previously reported optimal ranges (72-80% utilization). Thermal and water management became important factors of performance. The analysis of the stacked bars thermal scale exhibited that cruise operation was always provided with the best distribution, with 27% being excellent, 36% being good, and only 3% being in the Fail category. Conversely, sprint conditions experienced performance deterioration with 9% Fail and 18% Poor with emphasis on the stress during high-load demand. This point was further reinforced by the radar comparison with the highest balanced performance of the cruise on all six KPIs- net efficiency, voltage stability, hydration index, thermal uniformity, auxiliary load share, and degradation rate, or the factors in which sprint has almost two times the rate of degradation (0.012 V/1000h) than harbour mode (0.006 V/1000h). The auxiliary power management was also found to be important because of the system-level optimization. Findings indicated that auxiliary loads prevented 11% of total power in harbour mode but increased to 16% with sprint conditions, which directly decreased net output by as much as 5% points. With these parasitic requirements factored in, the net system efficiency drops to 91% in cruise mode to 86% in sprint mode, and the cumulative cost of both degradation and energy diversion is combined. These results show that to establish successful maritime PEMFC implementation, optimization on both system level (auxiliary subsystems) and stack level (thermal and water balance) is necessary. One of the last significant contributions of the work is the introduction of multi-dimensional visualization tools to provide the definition of safe operating envelopes. The results, including 3D surfaces and threshold planes, give the engineers actionable boundaries: hydration collapse below 40% relative humidity or huge load overheating above 2.5 bar pressure; efficiency can be maintained above 0.84 but not above 0.88; hydrogen utilization can be operated in 70-82. These objective limits are used to fill the gap between laboratory experiments, which tend to concentrate on one parameter, and in the real-world of the sea, where more than one variable is at work at the same time. Overall, this paper shows that under the conditions of maritime applications, PEMFCs may be highly efficient and fuel-consuming, but the long-term performance should be grounded in the consideration of the quantitative safe zones in this paper. It is more effective than the previous studies that have focused on general efficiency ranges and water management issues, because the current paper offers operational envelopes of operations, which have operational boundaries and are based on multi-variable simulations. The larger understanding is obvious: to effectively decarbonize maritime transport with the help of PEMFCs, technological development will be necessary, not only to achieve success but also to optimize the system properly with the help of such structures. This research sets a practical roadmap towards the development of stable, effective, and sustainable PEMFC implementation in the maritime industry by measuring the trade-offs in operations and defining limits. Further studies will concentrate on experimentally validating the proposed simulation model in a real maritime operational environment. Developing a scaled PEMFC test bench capable of emulating the shipboard temperature, humidity, and dynamic load changes is required to validate design design-predicted efficiency band (0.84–0.87) and the specified safe operating windows. The validation is necessary in order to bring the theoretical findings into practical guidelines for marine fuel cell development and to quantify the relationship between predicted degradation trends and real electrochemical aging behavior. Another potential solution is a combination of the adaptive controller and energy management system with the PEMFC stack. Advanced control techniques, for example, model predictive control (MPC) and hybrid AI-based optimization, are able to adaptively optimize the performance of thermal and water subsystems as a function of varying load requirements and environmental conditions at sea. The inclusion of these control schemes in the system design will improve real-time performance stability and, similarly, increase potential operating life by eliminating stresses normally induced during maneuvers or propulsion transitions. Lastly, future research must investigate hybridization and on-board system integration (linking PEMFCs with renewable sources such as photovoltaic arrays, energy storage systems, or auxiliary reformers). This could provide redundancy, increase energy security, and lower total emissions in port and cruise operations. This experimental and system-level work will be critical to moving towards commercial-scale delivery and continuing the global transition to low-emission maritime power solutions.

Declaration of competing interest

The authors declare no conflicts of interest.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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