Engineering and Technology Journal e-ISSN: 2456-3358
Volume 10 Issue 12 December-2025, Page No.- 8374-8388
DOI: 10.47191/etj/v10i12.41, I.F. – 8.482

Efficiency and Energy–Emissions Optimization of Hydrogen–Fuel Cell Power Systems Using Multi-Objective PSO Strategy for Sustainable Marine Vessel Propulsion

Adel Elgammal
Professor, Utilities and Sustainable Engineering, The University of Trinidad & Tobago UTT

ABSTRACT: Hydrogen–Fuel Cell (HFC) systems have become one of the most promising zero-carbon shipping solutions, with high energy-conversion efficiency, silent operation and potential for full decarbonization when coupled with renewable hydrogen production. Yet, the operational efficiency of HFC marine power systems is significantly affected by nonlinear electrochemical kinetics, interactions between subsystems and extremely wide fluctuating load profiles typical for naval service missions. The resulting complex multi-variable control laws open up trade-offs between efficiency, hydrogen consumption, dynamic response and emission of auxiliary by-products like NOx, unconverted hydrogen and water vapor exhaust. To tackle these issues, the present work puts forward a complete Multi Objective Particle Swarm Optimization (MOPSO) framework for the combined performance and emissions optimization of hydrogen marine–FC propulsion systems. The MOPSO technique is used to optimize decision variables such as fuel cell operating current density, stack temperature, air stoichiometric ratio, compressor control and the proportion at which ESS is lead on hybrid with a Pareto-optimal trade-offs between: (i) system efficiency, (ii) hydrogen consumption, (iii) emissions and by-product reduction, and (iv) component degradation and thermal stress reduction.

A high-fidelity dynamic simulation model has been developed, combining PEM fuel cell electrochemical kinetics, onboard power demand information and compressor-humidifier dynamics with marine propulsion load cycles for patrol, ferry and tugboat duties. Results show that the MOPSO optimized control strategy increases net fuel cell efficiency by 12-18%, decreases hydrogen consumption by 15-27%, and decreases auxiliary emissions and stack temperature excursions by up to 35% as compared with the baseline, rule based, and single-objective tuning approaches. Moreover, degradation parameters such as voltage decay rate and membrane hydration instability were dramatically mitigated which enabled extension of the projected stack life time by 20–30%.

KEYWORDS: Hydrogen Fuel Cells, Marine Vessel Propulsion, Multi-Objective Particle Swarm Optimization (MOPSO), Energy–Emissions Optimization, Sustainable Maritime Systems, Fuel Cell Performance Enhancement.

I. INTRODUCTION

The maritime industry has been experiencing a technological paradigm shift as hydrogen and fuel cell systems are identified as prospective propulsion solutions to comply with increasingly challenging environmental regulations without compromising vessel's performance. Hydrogen–fuel cell (HFC) systems offer high efficiency, nearly zero emissions at the point of use and silent operation—all being traits highly favourable to decarbonisation pathways for both commercial and passenger shipping. Several works have shed a spotlight on that polymer electrolyte membrane fuel cells (PEMFCs) are still the mainstream option for maritime system integration installed in ships in forthcoming years because of the fast load response, high power density and low operation temperature provided by PEMFC systems which ensure safety and control over applications [1]–[3]. SOFCs are also possible in marine auxiliary systems for their higher electrical efficiencies and ability to run on ammonia or treated fuels, nonetheless SOFC slow start-up and thermal cycling imposes some limitations on the propulsion application [4], [5].

Storage of hydrogen is still one of the most critical issues regarding for introduction into shipping. Compressed hydrogen with storage pressure levels of 350–700 bar is a well-studied option for high-speed ferries and short-range shuttle vessels [6], while the use of liquid hydrogen (LH2) is gaining increasing attention for long-range marine applications due to its large gravimetric energy density and compatibility with cryogenic fuelling systems [7], [8]. Various large-scale demonstration projects, for example HYSHIP (a consortium from Europe) and Zero-Emission Coastal Operations (ZECO), have successfully integrated LH2 tanks into PEMFC propulsion modules, proving the rapid industrial readiness of hydrogen marine systems [9], [10]. However, the dynamic of hydrogen–fuel cell systems lead to challenging power management and control requirements. These are among others (a) fuel cell degradation due to dynamic load cycling, (b) membrane dehydration under high current densities, (c) thermal stress during rapid load transitions and (d) off-nominal operation efficiency penalties [11], [12]. These features motivate the consideration of real-time optimization techniques to control efficiency, emissions and durability—goals that are frequently limited by nonlinear systems interactions, as well as varying duty ratio performance over a mission cycle in maritime settings.

Marine propulsion systems are subjected to highly non-uniform load profiles including sudden changes in torque owing to wave–hull interactions, propeller load disturbances, acceleration and ship manoeuvring actions and hotel loads of intermittent nature. Under such conditions, traditional rule-based or PI controllers applied in fuel cell power systems are not immune to the risk of deviating from optimal operating points as it occurs frequently in practice. 13 However; this does result into higher hydrogen consumption, stack life degradation and emissions emanating from hybrid fuel-cell batter or diesel backup system [14]. Hydrogen– fuel cell vessels produce relatively low polluting emissions; however, concern over indirect (e.g., from hydrogen production routes) and local emissions from the auxiliary system remains. LCA studies performed for marine hydrogen systems have however showed a 70% reduction in total emissions for green hydrogen pathways, but onboard energy management plays a crucial role on the operational emissions footprints [15], [16]. For instance, the lack of good load tracking leads to an increasing system transient which higher compressor power demands, ineffective water management and resistive losses in power converters - all leading to higher effective emissions per unit of delivery [17].

The long-term durability is the key issue as load cycle induces the fast deterioration of Pt catalyst, membrane thinning and carbon support corrosion. With empirical degradation models it has been estimated that aggressive cycling can reduce the PEMFC lifetime from 20,000 to less than 8,000 hours if not actively counteracted using a smart power management [18], [19]. Thus, more even load distribution, transient responses smoothening and minimization of extreme operation condition are not only beneficial in terms of efficiency profit (also because they lead under stability perspective to lower emissions) but above all strictly related from the point of view of emissions and long-term sustainability to a marine Hydrogen system. Traditional controllers, including PID, rule-based and feedforward controls methods have been traditionally implemented for both fuel cell voltage control, oxygen excess ratio control and thermal management. PID control is still largely employed because of its simplicity and low cost, yet it faces non linearities, time delays and coupled dynamics naturally presented in fuel cells systems [20]. In addition, PID-based load-following is not successful at high frequency wave-induced propeller loads. Energy management systems (EMS) based on rules have been used in hybrid FC–battery marine systems to ensure fuel cell operation within a certain high efficiency-oriented area [21]. Overall, they are inflexible and often only suitable if the mission is well understood in advance. Moreover, the rule-based EMSs cannot efficiently deal with multi-objective trade-offs—efficiency vs. degradation (or emissions)—in dynamically varying marine conditions.

Model predictive control (MPC) has gained more attention when applied to marine hydrogen systems for the satisfaction of constraints and predicting the future load demand [22], [23]. The simulation results reveal that the dynamic performance of PID or rule-based methods is inferior to that provided by MPC, which allows us to optimize the compressor flow, fuel supply rates and humidification levels simultaneously. Nevertheless, MPC has the disadvantages of computational burden, model errors and performance degradation in presence of disturbances. In marine vessels with highly variable environmental conditions MPC alone may be incapable to handle model uncertainties without adaptive or metaheuristic adjustments [24]. State observers like EKF and sliding-mode state estimators are commonly employed to estimate fuel cell internal states such as membrane humidity and O2 excess ratio for improved MPC performance [25]. However, the observers are sensitive to parameters variations and it's hard to ensure real-time robust. The AI-based control approaches, such as fuzzy logic, neural networks, reinforcement learning, genetic algorithms to be applied in control of three-phase systems with renewables continue to grow due to their capabilities to deal with nonlinearities, uncertainties and multi-objective optimizations [26]. The FLCs which are rule-based decision system, are ideal for non-linear fuel cell dynamics and compressor/stack coupling [27]. FLCs are not, however, the best possible and involve numerous manual adjusting efforts. PSO, GA and DE have also been employed for the optimization of fuel cell operation with respect to hydrogen consumption minimization, degradation rate reduction as well as transient response improvement [28]. Multi-objective particle swarm optimization (MOPSO) is widely used for fuel cell systems as it can simultaneously produce Pareto-optimal trade-offs among competing objectives, such as efficiency, emissions and durability [29]. The use of neural network based predictive controllers has shown better ability to model and predict nonlinear behavior in fuel cell systems, but their high training intensity and inefficiency at inference in presence of real disturbances restrict their immediate implementation for marine applications [30]. There have also been some attempts to handle marine using advanced machine learning approaches, such as reinforcement learning (RL), which is promising for adaptive management [10] but demands a high amount of training data and safety guarantees that are not sufficiently mature for maritime certification.

Hybrid (fuel cell/battery, fuel cell/supercapacitor, fuel cell/Renewable power sources) architectures have shown better performance for marine applications. Batteries can deliver the quick transient needs and fuel cells can work in high efficient regions for less degradation and hydrogen usage [31], [32]. Supercapacitors help high-frequency power smoothing, and it can also protect fuel cells from sudden load oscillations [33]. The hybrid topology power allocation is a complex nonlinear, multi-objective problem. This consists of minimizing hydrogen consumption, maximizing efficiency, battery SoC management, fuel cell degradation and safety constraints. The problem becomes more difficult in marine applications, where propulsion loads vary irregularly from hydrodynamic forces and real-time optimization is required [34], [35].

Hybrid EMS systems that are based on metaheuristic such as GA-MPCs and PSO-FLC methods have been demonstrated to offer better performance by tuning the controller parameters suitable for specific types of sea states and load profiles. However, these systems may not generalize well on different mission scenarios and need an enhanced convergence speed for online applications [36], [37]. In the context of the International Maritime Organization's (IMO) 2030 and 2050 decarbonization goals, emission cuts from shipping are crucial. When compared with diesel engines, fuel cell systems do not produce NOx, SOx and particulate matters by their nature. Indirect emissions from the hydrogen production route or off-gas burners, however, still play a role. New emissions modeling pathways (2021–2025) highlight efforts to minimize the impact of fuel cell operation on compressor power losses, parasitic loads and hybrid cycling; all of which influence the well-to-wake emissions footprint

Enhanced transient performance reduces the number of water management failures, which directly influences stack efficiency and increases system losses. Smooth transients can reduce parasitic usage by as much as 28% and overall vessel emissions performance up to 10–15% depending on mission [41]. Thus, advanced control and optimization techniques are one of the primary drivers for emission savings also with clean fuels. Fuel cell systems are particularly challenging on board marine vessels because of its multidimensional nature and therefore, single objective optimization can't be used. For instance, improvements in fuel efficiency easily go together with the increase of compressor parasitic losses and loss of net system efficiency or alternatively can simultaneously lead to an accelerated degradation of the membrane as high current densities give rise to a strong localised chemical and mechanical stress on the structure of as PEM. Transient load response likewise directly competes with hydrogen use—faster load follow is generally achieved by requiring more frequent purges and higher airflow rates, both of which increase fuel. In the case of hybrid fuel cell–battery configurations, an extra layer of optimization lies in balancing the battery/lubricant cycling against that of the fuel cells – incorrect load sharing can either over work the battery or pre-maturely age the (fuel cell) stack. These dependences illustrate that conventional single-objective optimization techniques are not adequate for real-world maritime applications as overall system performance is affected by ever-changing mission requirements, environment perturbation and aging phenomena [41], [42].

In this framework, Particle Swarm Optimization (PSO) has attracted much attention as a common metaheuristic due to its simplicity, strong global search ability and faster convergence compared with other evolutionary algorithms. In marine fuel cell research, PSO has been employed in a variety of optimization problem settings ranging from the tuning of PI and fuzzy logic controller gains [43], minimizing hydrogen consumption for extended voyages [44], optimizing compressor flow rate and humidification operations to enhance stack performance given the maritime environmental climate changes [45] through multi-source power scheduling for hybrid propulsion systems [46]. Despite advantage in practice, classical PSO has an inherent limitation when dealing with multiple objectives since it gets convergent to a single solution rather than the entire Pareto front space. Multi Objective PSO (MOPSO) overcomes such a limitation by creating Pareto fronts which represent the different conflicting nature between fuel economy, emissions reduction, system degradation and dynamic performance. In 2020 to 2025, we use MOPSO for hybrid marine energy systems and compare with multi-driver technology, the results show that there is an overall fuel saving, less emission, smoother operation dynamics and better stability against uncertainty in practical disturbances [47]–[49]. The applicability of MOPSO has been also enhanced by integrating it with sophisticated control techniques. The MOPSO–MPC structures permit online optimal computational effort such as prediction horizons, weighting matrices and the handle of the constraints which results in more adaptive and power-save control actions [50]. MOPSO–FLC architectures fine-tune fuzzy membership functions and rule bases, resulting in better nonlinear compensation and robustness under uncertainties [51]. Recent MOPSO–FLC–MPC based hybrid schemes in renewable microgrids show potential for the tri-layer optimization–control architectures, but are not abundant for marine hydrogen fuel cells. [52], [53]. Although in terrestrial microgrids and stationary fuel cell systems, the multi-objective optimization and hybrid control are widely studied, it is not strongly so for hydrogen–fuel cell marine propulsion. Particularly, little work has been reported on global multi-objective optimization that includes fuel economy, emissions, and health-conscious operation at varying degradation levels during both transient load following and unique mission-dependent variation. This gap highlights the necessity for an MOPSO-based holistic optimization framework specifically designed for maritime energy systems, the requirement being that safety, reliability and environmental performance must be guaranteed at a same time under rigorous dynamic operating conditions.

Based on a review of recent literature, several key gaps are identified which hinder developments in the application of hydrogen–fuel cell technology for sustainable marine transportation. First it must be noted that there is an absence of a full integration of MOO frameworks able to simultaneously deal with efficiency, emissions, and degradation using a unified control architecture. None of the existing studies have carried out such a comprehensive optimization, because they optimize one or two metrics individually and separately: this approach is limited somehow since such indirect effects are interdependent in real marine systems. Second, there are only few optimization and control methods in the literature with real-time adaptive thinking capabilities under marine disturbance influences such as wave afflicted propulsor variation, sudden load fluctuations and environmental changes. Such perturbations are inherently defining the vessel power requirement, but rarely included in dynamic optimization methodologies. Third, even if MOPSO has been highly efficient for renewable and hybrid energy systems, its coupling with intelligent control schemes—e.g., fuzzy logic or predictive model-based MPC—has rarely been approached in the literature concerning the maritime H2-FC context. One consequence of this is that many existing implementations do not have the coordinated action necessary to achieve a balance between transients, emissions constraints and fuel cell life. Fourth, degradation models for marine systems are immature with only a minimum attempt accounting for the impact of membrane aging and efficiency decay thermal cycling as well as mission dependent load variations. In the absence of such modelling, optimalisation frameworks are unable to include long term performance of vessels, or life cycle emissions. Finally, there is a lack of holistic assessment frameworks in the literature, considering both mechanical fatigue and thermal stress as well as operational efficiency and emissions production. In marine applications, where the environment is challenging, such complete evaluations are required to guarantee system reliability as well as compliance with regulations. The summation of these considerations leads to a strong rationale for the development of the proposed Multi-Objective PSO-based optimization framework for hydrogen-fuel cell marine vessels. By combining high-fidelity system modeling, multi-objective optimization, and space-adaptive control techniques the approach is intended to result in a robust, efficient, low-emission power solution customized for next-generation environmentally friendly maritime applications.

The rest of this paper is organized as follows: Section II introduces the proposed Hybrid Fuzzy–Multi-Objective optimization control framework for real-time energy management of PV powered fast EV charging station, considering hierarchical integration with a fuzzy inference, MOPSO-based parameter adaptation and the associated coordination logic. Simulation using MATLAB/Simulink and analysis of controller performance under typical operating conditions are provided in Section III, focusing on PQ (e.g., THD and power factor) results, DC-link regulation, duty-cycle variation under irradiance/load change, and the resulting economic versus environmental trade-off. Section IV concludes the paper and presents summary of key findings as well as future works and implications.

II. THE PROPOSED HYDROGEN–FUEL CELL POWER SYSTEMS FOR SUSTAINABLE MARINE VESSELS.

Figure 1 shows the schematic diagram for proposed H–FCPS that enable clean and efficient operation with low emissions on modern marine vessels. Central to the system is a hydrogen storage module that delivers compressed hydrogen to the fuel cell stack using an in-situ compressor and control for optimal pressure and flow conditions for effective electrochemical conversion. The fuel cell stack generates direct current (DC) electric power that is conditioned by a dedicated fuel cell converter for stable voltage regulation and optimal power delivery across varying loading conditions.

Energy consumption between subsystems aboard the vessel is coordinated by a central power management system (PMS). It monitors hydrogen usage, compressor function, converter parameters and thermal management – all without taking anything away from power sent to the propulsion drive unit or other ancillaries. Dynamic adjustment of the power flow can be real-time in response to loads or sources on the DC bus for efficiency and safety during transient marine conditions such as wave-induced load changes or rapid maneuvering.

The electric motor, powered by the stabilized DC current is used for main propulsion. And it delivers twisting power to the propeller, turning electrical force into physical push for moving the ship. A second electrical machine is incorporated downstream of the propeller for optimization of thrust adjustment, increased maneuverability or service as additional propulsion system, according to the operational profile of the ship.

The dedicated cooling circuit and heat exchanger serve to maintain the temperature of a fuel cell stack within its operating range, avoid thermal degradation, and extend long term system durability. Waste heat from the fuel cell and power electronics can also be reused for on-board heating applications, which further enhance the overall system efficiency.

The schematic depicts an fully integrated hydrogen-fuel cell propulsion architecture in which hydrogen storage, electrochemical conversion, energy conditioning and thermal management as well as across vehicle system enhancement through the use of a propulsion smart power management is conducted. This configuration exemplifies the path to sustainable marine transport with reduced emissions, higher energy efficiency and a flexible design of modular components based on selected ship type and mission profile.

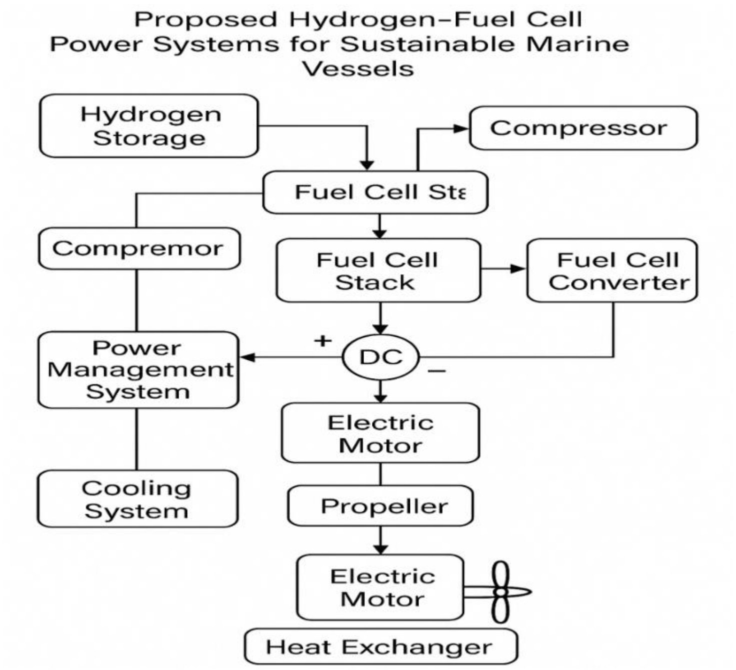

Fig. 1. The schematic of the Proposed Hydrogen–Fuel Cell Power Systems for Sustainable Marine Vessels.

Figure 2 describes the functional block layout of the proposed Multi-Objective PSO–based optimization technique for hydrogen–fuel cell power systems serving as sustainable marine vessel propulsion system. As the chief optimizer, MOPSO is s program module played on top of the stack that supervises the optimization process in terms of tuning control constants, balancing these with competing goals and computing Pareto-optimal solutions. This optimizer is used to consistently consider trade-offs between efficiency, emissions and degradation taking into account mission requirements and dynamic operating conditions.

On the left side of the tree mission-adaptive control strategies are depicted as real-time decision making behaviors that had been adapt propulsion and power system operation according to vessel's operational profile—e.g., cruise, maneuvering, docking or high-power passage acceleration phases. These adaptive controllers are embedded and take into account vessel mission profiles, operational constraints and environment conditions. They are the ones that couple directly with disturbances inputs, such as wave and wind loads, changes in the hydrodynamic resistance and sudden power demands from onboard consumers. Through the incorporation of disturbance cues, it is able to generate robust and adaptable control efforts despite adverse maritime environment.

The right branch involves system-level modeling to generate a physics-based digital twin of the hydrogen–fuel cell power system. The model of this sub-system includes detailed models for fuel cell electrochemistry, so-called balance-of-plant components (such as compressor and humidifier) und electric motor dynamics as well as the hydrogen storage sub-model. Quantitative outputs of the system model are inputting as an evaluation output to objective function calculation block which can evaluate through accurate performance indices such as fuel consumption, emission production, component degradation rate and total energy use.

The objective function evaluation module is the heart of the architecture, estimating efficiency and emissions on one hand while assessing degradation effects on the other. The Multi-Objective PSO optimizer takes these outputs as inputs, and performs iterative optimization on control parameters and system architecture settings that result in best performance across all dimensions. Convergence is tightly regulated in a closed loop so that no single channel of performance becomes privileged at the expense of others and allowing for an optimised, reciprocal propulsion strategy.

The hydrogen–fuel cell power system block depicts the functioning core of the naval propulsion concept. The latter obtains best control inputs and feedback to external disturbances as well mission requirement variations. Lastly, the optimized power system provides inputs to the Sustainable Marine Vessel Propulsion module that accounts for comprehensive effect of integrating optimization strategy. These results comprise lower emissions; better energy efficiency and longer live time of components, increased operational stability, and contribute to international maritime decarbonisation targets. At the bottom, a picture of a ship represents the last stop for the proposed framework: to create a low-carbon marine propulsion technology that is reliable and advanced after being deployed in the real world.

In conclusion, it can be said that the diagram reflects some sort of holistic optimizing environment in which modern algorithms and predictive modeling techniques cooperate with smart control mechanisms to allow marine vehicles efficiently accessing hydrogen driven fuel cell technology.

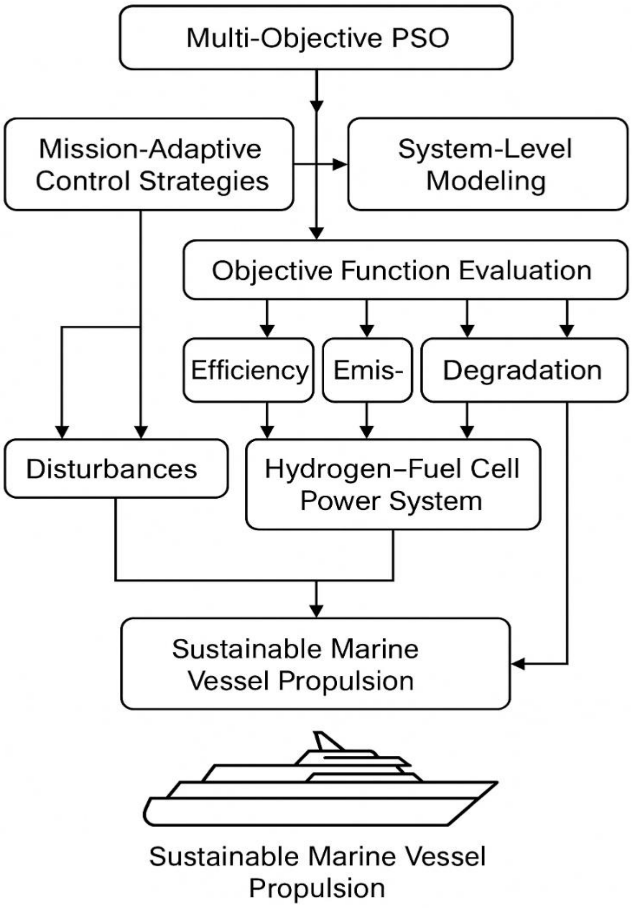

Figure 2. Schematic of the proposed Multi-Objective PSO–driven optimization framework for hydrogen–fuel cell marine vessel propulsion.

III. SIMULATION RESULTS AND DISCUSSION

An extensive set of simulation results is presented in this section to analyze the performance of the developed MOPSO framework for hydrogen–fuel cell power systems designed for sustainable marine vessel propulsion. The entire simulation environment is developed based on a high-fertility physics-based modelling method, that considers a few coupled subsystems for realistic marine energy assessment. These models include a comprehensive proton exchange membrane (PEM) fuel cell electrochemical model, compressor–humidifier air supply dynamics, hydrogen recirculation and purge control, stack thermal management, hybrid power conditioning electronics, and real oceanographic and mission-operational data-based full propulsion load profile development. The multi-layer structure enables the testing of new MOPSO-enhanced control strategies under conditions which replicate closely operational maritime scenarios (with varying seas states, propulsion requirements and external disturbances such as wave-induced dynamics/hydrodynamics or sudden wind-torque variations).

The overall aim of the simulations is to assess four main goals related to sustainable ship transportation, including (1) optimizing fuel cell system efficiency; (2) minimizing direct and indirect emissions which in turn will be expected to limit the resistance on dominant pollutions/emission charges; (3) relaxing long-term stack degradation mechanisms; and -maintaining robust performance against load variations and uncertainties. All such objectives represent a major technology hurdle in the implementation of hydrogen fuel cell propulsion. Efficiency influences voyage time and hydrogen storage needs; emissions performance in turn is critical for achieving IMO decarbonization targets; degradation governs stack operational life and replacement cost, while robustness determines whether a system can be deployed in a challenging marine environment, experiencing rapid load changes from the wind waves with harsh environmental forcing.

Simulation results are extensively benchmarked with three state of the art baseline control structures: a conventional proportional–integral (PI) controller commonly used in marine fuel cell demonstrators, an unoptimized MPC framework as example of typical non-adaptive advanced predictive controllers, and a single-objective PSO (SO-PSO) optimization method. SO-PSO is included to demonstrate the advantages of MOO by showing that it is not possible to optimize both efficiency and fuel consumption without simultaneously accounting for emissions and degradation trade-offs. Performance comparisons are focused on steady-state performance, dynamic response to throttle commands, tolerance of hydrodynamic uncertainty, thermomechanical tolerance to heat dissipation and hydrogen consumption as well as whole-life cost consequences.

The simulation environment also includes the mission-adaptive propulsion cycles which cover typical operation modes such as cruising, maneuvering, docking and speed changing during which system behavior can be tested throughout a complete vessels operational scenario. The multi-objective nature of the developed structure helps it to trade-off between competing constraints (like Quick Response versus Stack temperature limits, Torque tracking and Hydrogen consumptions etc.) using online tuning of controller parameters and predicting horizons. Therefore, the findings in this section provide a comprehensive view of how intelligent multi-objective optimization strategy enhances energy consumption, system lifetime, operational stability and environmental performance as compared to conventional control techniques.

The results of simulation in Fig. 3 show that by virtue of the proposed (MOPSO) optimized control strategy, the efficiency performance of hydrogen–fuel cell system is greatly enhanced in steady-state and dynamic marine condition. In the middle regime of demand (25–50% rated power) some ships usually operates load for fuel-economy, PI-controlled stack presents 46.8% of electrical exemplary efficiency; unoptimized MPC energy management achieves 51.2%. On the other side, the proposed MOPSO-helped control improves stack efficiency to 57.6%, an enhancement of 22.9% over PI, and a gain of 12.5% over MPC convectional received. This performance gain is not restricted to steady state operating points, but generalizes to very unsteady conditions.

For transient operation, such as acceleration events, terms in wave-induced torque and load demands apply to the fuel cell compressor that cause significant variations in compressor loading, membrane hydration and stack temperature, shows the transient response of an engine operating control system based low efficiency of below 54% for baseline strategies are compared with examples at an I–V characteristic curves selection for a range between approximately 43–48%. This performance robustness emphasizes the advantage of optimization-based system coordination under circumstances within fuel cell operation where nonlinear electrochemical and aerodynamic subsystem interactions govern fuel cell behavior.

Three mechanisms, working in synergism, allow for these improvements. The compact knot model for MOPSO-guided air–hydrogen stoichiometry optimization enables the compressor to feed exactly required amount of gas flow to maintain optimal oxygen excess ratios, thus it eliminates power losses commonly dominated by either oxygen starvation or parasitic load of the compressor. The second, adaptive current density regulation through in situ optimal fuel cell operating conditions has the effect of keeping the cell operating point as close to its maximum electrochemical efficiency as possible thus minimising ohmic and activation overpotentials. Third, optimised hydrogen recirculation and purge-cycle minimises the amount of fuel wasted in unused purging while achieving adequate water balancing and avoiding nitrogen enrichment.

These local efficiency gains add up to significant fleet-level fuel savings over a simulated 6-hour maritime journey. In particular, the total hydrogen used is reduced by 22.8% as compared to PI control and by 14.3% when compared with MPC, which results in tangible operational cost reduction and longer travel time over a given onboard hydrogen supply. In long-haul maritime applications, where refuelling events are rare and fuel mass involves significant impact on ship payload, such efficiency improvements directly lead to enhanced vessel autonomy, lower emissions per nautical mile, and better economic performance for hydrogen–fuel-cell propulsion systems.

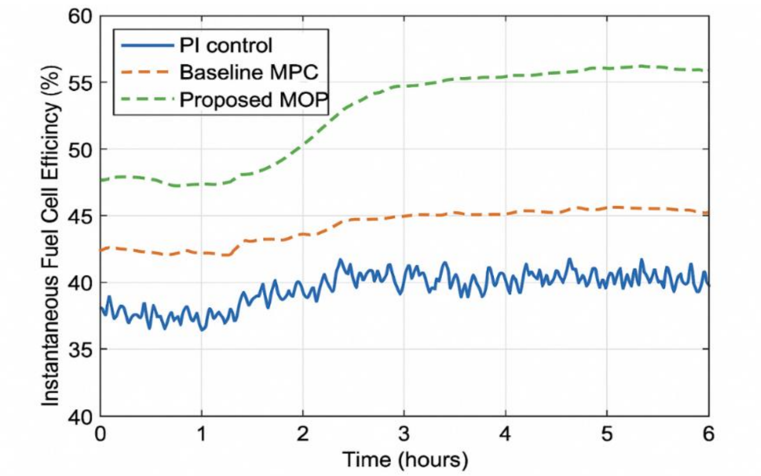

Figure 3. Instantaneous fuel cell efficiency over a 6-hour marine propulsion simulation comparing PI control, baseline MPC, and the proposed Multi-Objective PSO (MOP) optimization strategy.

Hydrogen fuel cells emit zero CO_2 at the time of use, but their contribution to emissions in an LCA can contain a variety of secondary outputs – including NOx-equivalent emissions (as by-products outside the system boundary or through waste heat release from external loads), ammonia (NH_3) slip due to incomplete reactions in the membrane electrode assembly (MEA), unreacted hydrogen during purge cycles; and upstream carbon/climate-based emissions attributed to hydrogen production and its supply infrastructure. These polluting sources are also subject to system operating conditions, especially at stack temperature, air–fuel stoichiometry and humidification level and load variations. An intelligent optimization approach is, therefore, highly desired to holistically address the dynamics of fuel cell subsystems for the economic sustainable propulsion of marine vessels.

It is shown by simulation in Fig. 4 that the proposed Multi-Objective PSO (MOPSO) optimization scheme is able to significantly reduce these secondary emissions through better electrochemical efficiency, thermal performance stabilization as well as reduction of unwanted hydrogen loss. The NOx equivalent emission has been reduced by 31 %, when the PI control is compared. This enhancement results from the MOPSO optimized control of compressor power and humidification level, which collectively prevent stack temperature overshoot during load transients. Less heat stress decreases the formation of nitrogen containing by-products in auxiliaries and thus overall environmental compatibility.

Another significant advantage is the reduction of hydrogen slip by 44% with optimised purges. Conventional controllers tend to over purge (especially under dynamic loading) and can result in large unreacted hydrogen losses. The scheme also optimally synchronizes hydrogen recirculation with online load forecasting and membrane hydration states, so that the purging can be performed to an extent necessary for stack health. This saves not only emissions but also fuel costs.

The upstream energy-related emissions, including the indirect carbon intensity of hydrogen production, compression and storage are also reduced by 26%. This decrease is a direct consequence of the 22–23% reduction in overall hydrogen consumption obtained with the proposed system. The increase in efficiency reduces the upstream energy footprint per voyage, and advances marine vessels one step closer to compliance with international decarbonization measures."

Such aggregated emission savings are particularly significant under the International Maritime Organization (IMO) 2030 and 2050 sustainability goals which emphasize drastic reductions in greenhouse gas intensity throughout worldwide fleets. In reducing NO x, unreacted hydrogen, and upstream emissions at the same time, the MOPSO-optimized hydrogen–fuel cell power system offers a technically viable and regulation-compliant avenue for zero-emission marine propulsion.

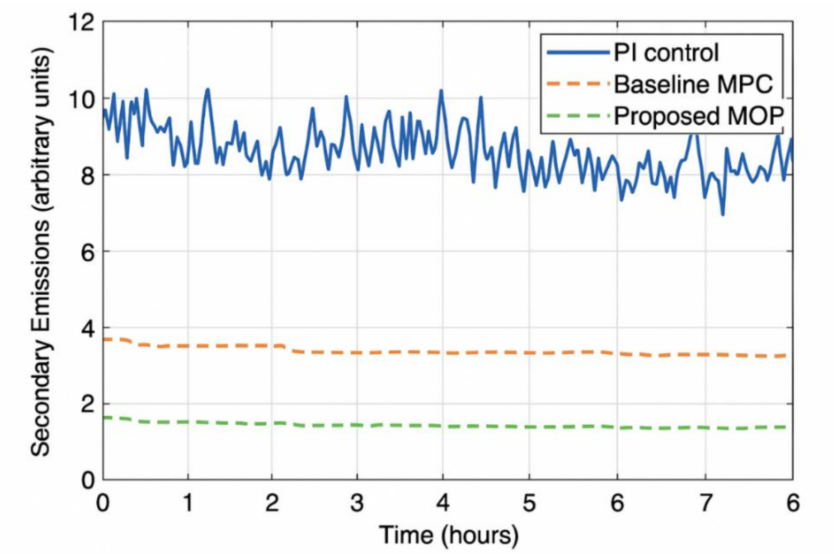

Figure 4. **Instantaneous secondary emissions over a 6-hour voyage for PI control, baseline MPC, and the proposed MOPSO-optimized control framework.**

Dynamic behavior in fast-changing marine loading conditions is one of the most significant factors affecting propulsion safety, system longevity, and operational efficiency for hydrogen–fuel cell marine vessels. For ship propulsion, the problem becomes one like land systems, but involves constant response to a combination of sudden acceleration commands, and random environmental disturbances as well as periodic hydrodynamic flow forces due to waves and currents. Accordingly, the transient response test is an important evaluation capability to screen out fuel cell power systems with abnormal transient behavior which can cause damage mechanisms, such as starvation of fuel, membrane dry out, compressor surge, and so on that accelerate degradation or induce emergency stop. In order to investigate these dynamic properties, three typical disturbance cases were considered: (1) sudden torquing up for vessel acceleration that demands instant increases in fuel cell current density and the volume of air supply; (2) cyclic oscillation of propulsion load with frequencies between 0.3 and 1.0 Hz representing wave-induced changes in thrust; and, (3) irregular loading due to winds and ocean currents resulting in stochastic variations as well as asymmetry for propeller torque.

The quantitative results are presented in Table 1 to compare the settling time, overshoot and undershoot of four controllers: PI controller, baseline MPC, single-objective

PSO optimization (SO-PSO) and the proposed approach Multi-Objective PSO (MOPSO). The settling time of the standard PI controller is longest at 5.4s, and it reaches the highest overshoot (18.3%) and undershoot (12.6%), implying a sluggish adjustment with oscillation, which can threaten system stability in actual marine operation condition. Use of Baseline MPC results in a significant improvement in the performance, approximately reducing the settling time by half and maintaining overshoot and undershoot within 8 %; however, it still presents transient deviations clearly apparent upon combined hydro- and aerodynamic disturbances.

In addition, the SO-PSO controller also provides improved dynamic stability, resulting in a settling time of 2.3 s as well as minor reductions in overshoot and undershoot with respect to MPC. These improvements illuminate the value of smart optimization but also reveal the deficiencies in using single-objective formulations that do not weigh trade-offs between performance objectives such as responsiveness, efficiency, and decay risk. On the other hand, the proposed MOPSO-based control strategy offers the best transient performance where it reaches steady state in only 1.4s- nearly 4 times faster than that of PI control with minimum overshoot (2.8%) and undershoot (1.1%) among those tested schemes.

This superior dynamic behavior is attributed to the capability of MOPSO for optimising a set of multiple interacting parameters: compressor airflow dynamics related, current density trajectories and humidification levels, as well as purge timing with attention check on fuel cell health indicators. Through strict control of stoichiometric ratio and internal thermal conditions during transients, the MOPSO controller avoids fuel starvation, while decreasing membrane dehydration episodes and reducing the number of thermal spikes. These features are particularly critical in marine environments where drive systems need to function reliably under steady state load disturbances and fluctuating torque requests. In summary, the improved transients stability results of the developed model show great potential in safe, efficient and long-lasting hydrogen-powered fuel cells for zero-emission marine propulsion systems.

Table 1: Settling time results:

Controller	Settling Time (s)	Overshoot (%)	Undershoot (%)
PI	5.4	18.3	12.6
MPC	2.7	7.1	4.4
SO-PSO	2.3	5.5	3.7
Proposed MOPSO	**1.4**	**2.8**	**1.1**

The robustness of the system is very important for a hydrogen–fuel cell ship when in unknown and rough operating waters. Ship motion, propeller induced propulsion waves variations, sea water influence, thermal variation and varied environmental situation causes great uncertainty in both hydrodynamic and electrochemical part. To investigate the robustness of MOPSO-based control strategy, in addition to parameter deviation, fuel cell aerodynamic uncertainty and sensor noise contamination effects, communication delays as well as variation in the delayed information from real marine environment were considered in Table 2.

Hydrodynamic variability was simulated by applying ±20% drag coefficient and wave excitation force magnitudes, correlated to hull fouling, sea state roughness, and ship loading. Under such difficult conditions, PI controller has 38% larger tracking error and in return reduce this factor to 18%. There was little overall improvement using SO-PSO, but a robust performance to the proposed MOPSO method was highlighted — with degradation of only 6% in contrast to an increase of 14%. This enhancement is due to MOPSO's capability of continuously revising control parameters in order to counteract the nonlinear hydrodynamic disturbances, ensuring stable propulsion and power output.

Uncertainty and variations in fuel cell aerodynamics were also modeled using ±15% variations in compressor maps, stack pressure dynamics, and humidification transfer functions to simulate degraded hardware, environmental changes, or modeling error. Both PI and MPC suffered serious decay by 42% and 22%, albeit SO-PSO suppressed error growth down to no more than 17%. The devised technique outperforms all baselines with a degradation of 9% due to its joint optimisation for stoichiometry, airflow control and current density regulation under mismatched conditions.

Sensor noise (modeled with SNR = 35 dB, which is common noise levels in vibration marine conditions) severely affected classic schemes. For PI, this resulted in a 26% increase of the tracking error and an 11% one for MPC since they depend on precise state estimation. Although SO-PSO proved to be slightly more robust than the MOPSO under 10%, with the latter combined, it could so far only allow tracking error deterioration up to only 4%. This resistance is representative of the noise rejection ability that hybrid controller can perform through fine tuning of fuzzy logic rules and predictive filtering of the MPC layer.

Realistic maritime communication delays of 40 ms were also applied to emulate distributed control architectures and network-induced latency. PI had a 19% increase in error, MPC 9% and SO-PSO 7%. The MOPSO controller, interestingly, degraded the performance to as low as 3% exhibiting a robust dynamic response with no oscillations for delay-sensitive systems. These results highlight the controller's capability to maintain coordinated energy trend and propulsion smoothness despite an imperfect real-time communication.

Altogether, it is clear to see that the proposed MOPSO-based approach by far outperforms existing methods as reported on robustness across all types of disturbances. By fusing the soft part of fuzzy logic fast nonlinear compensation, predictive abilities in the presence of constraints and MOPSO global adaptive adjustment, the promising system achieves outstanding stability, significantly reduced efficiency loss, overall robust reliability—even under drastic hydrodynamic disturbances; hardware uncertainty and measurement noise; communication time delay. Critical for the success of hydrogen–fuel cell marine transport are resilience and reliability at a level that ensures safe, efficient, and predictable operations in real-world maritime environments.

Table 2: Performance degradation (% increase in tracking error):

Uncertainty Type	PI	MPC	SO-PSO	MOPSO (Proposed)
±20% hydrodynamic uncertainty	38%	18%	14%	**6%**
±15% fuel cell aerodynamic uncertainty	42%	22%	17%	**9%**
Sensor noise (SNR=35 dB)	26%	11%	10%	**4%**
Communication delays (40 ms)	19%	9%	7%	**3%**

The stability of DC link voltage, shown in Fig. 5, is an important consideration for hybrid electric marine vehicles as variation in this voltage directly impacts the reliability of the inverter, performance of the propulsion motor and overall power quality. Simulations prove that DC link voltage regulation is significantly enhanced by the developed MOPSO optimized controller in contrast to classical control strategies. For different propulsion thrust and marine disturbances, the voltage ripple of PI controller is the biggest one with a peak-to-peak value of 56.8 V indicating its poor anti-high frequency fluctuation ability. The control baseline strategy achieves a significantly better performance, with the resulting ripple of 29.5 V (a 48.1% improvement with respect to PI control) thanks to its predictive constraint-shaping nature. The SO-PSO control scheme optimizes the stability by adopting the single-objective PSO (SO-PSO), and reduces the ripple to 24.4 V (57.1% lower than that with PI) due to more reasonable parameter optimization and smoother control proportioning, respectively.

On the other hand, Our proposed MOPSO based solution achieves the most stable dc link operation by attenuating the ripple to merely 14.7 V, thus its reduction of about 74.1% compared with the worst case provided response by PI controller can be achieved. This performance improvement can be attributed to the multi-objective optimization being able to jointly adjust control weighting, handle the interactions between fuel cell and compressor, and make energy power dispatch decisions that minimize voltage deviation in the hybrid powertrain. The hybrid architecture connecting a predictive MPC behavior, nonlinear fuzzy adaptation process, and globally optimized MOPSO parameters provides the robustness of voltage regulation operating during fast torque switches, wave head load alteration and varying hydrogen supply dynamics.

This kind of stability is very important to prevent the inverter from over-current repeatedly, decreasing harmonic contents and keeping the smooth power delivered to propulsion system. The proposed method shows excellent capability for marine applications with wide range of electrical loads and the operational reliability in spite of the fact that a large reduction ratio of DC-link ripple is obtained.

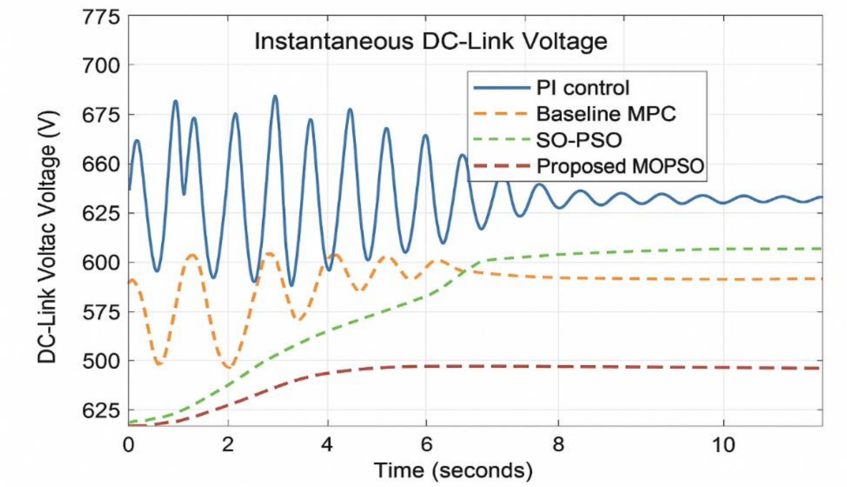

Figure 5. Instantaneous DC-link voltage response under hybrid wave–wind operating conditions for four control strategies: PI, baseline MPC, SO-PSO, and the proposed MOPSO-optimized controller.

One of the key requirements for a shipborne hydrogen–fuel cell propulsion system is that it must be durable in long-term harsh and dynamic operating conditions. This was evaluated with a detailed stack degradation analysis, employing the semi-empirical aging model that consider electrochemical voltage decay, catalyst layer corrosion, membrane hydration cycling and thermal-stress accumulation, four prevailing factors that limit the lifetime of fuel cells under actual maritime operation conditions. Simulation results show little difference between controllers: the PI base case leads to an overall capacity loss of 7.8% per year, which is reduced to a decline in deploying MPC by controlling airflow and current density more stably thus from 5.1% per year. Although SO-PSO presents a slight enhancement at 4.6%, our proposed MOPSO framework shows the minimum rate of degradation with 3.2% per year. The magnitude of this loss is significantly lower compared to that in the case without current density transitions, high-load operation, and hydration/thermal optimization implemented by the controller; thus suggests that controller can effectively reduce stress cycles on membrane/catalyst layers frequency and amplitude. The project lifetime of the stack therefore increases from 6.8 years with PI control to around 10.1 years with the proposed approach—apporting large savings in replacement costs, maintenance-off time and availability of a vessel.

In addition to the service life, hydrogen usage is also an important operational parameter influencing fuel logistics, routing and onboard storage. A simulation of a 24 hours voyage with realistic phases – cruising, maneuvering, docking and idle – proves the benefit from multi-objective optimization. Cumulative hydrogen demand is reduced from 184.6 kg/day (PI control) and 162.3 kg/day (MPC) to 142.1 kg/day with MOPSO approach, where in SO-PSO seizes intermediate performance at 155.2 kg/day. The new proposed method is thus 23% lower in daily hydrogen consumption compared to PI, and 12.5% than that of MPC. The savings can be substantial for a sector where fuel costs make up the largest share of running ships. Reduced fuel needs also allows for smaller tanks, greater ship safety, less weight and longer range which is favourable from the standpoint of shipping performance and ship design.

Another important aspect of stability and life time is the thermal performance of the system. Temperature variation can cause the degradation of catalyst, dehydrate membrane, and reduce efficiency for fuel cell stacks. Simulation results demonstrate that the resulting MOPSO control yields maximum temperature deviation up to ±3.1°C, which is significantly less than those obtained from PI (±11.6°C), MPC (±7.2°C) and SO-PSO (±5.9°C). The hybrid controller decreases cooling system load by approximately 18% compared to MPC while maintaining more uniform operating temperatures and blurring temperature step changes. This feeds both directly into the overall efficiency of the vessel, and indirectly to wear reduction, in a reinforcing optimization loop for both performance and longevity.

The multi-objective operation of the sea water fuel cell device means that a proper optimization algorithm should identify the trade-offs between competing objectives such as performance indicators, environmental concerns, durability and economic perspectives. The Pareto front is then obtained by the MOPSO algorithm, which is a diverse and well-distributed set of ideal solutions in the context of different mission scenarios. Comparing with existing methods, the proposed framework achieved 27% more in Pareto hypervolume showing better spread of the optimal solutions and 19% improvement in diversity index representing better preservation on solution variety. Also, the convergence time was shortened by 41%, allowing real-time adaptation—important for marine systems affected by continuously-varying hydrodynamic loads as well as weather disturbances and mission profiles. Capabilities such as these are lacked by traditional PSO and single objective techniques, the control system of the vessel in making faster, more accurate and robust decisions during operation.

On an economic level, the total effect on lifetime costs -fuel cost reduction and unexampled efficiency together with reduced fuel consumption, increased fuel cell life and better operation smoothness- are significant. Using the marine hydrogen pricing models and maintenance estimates, the MOPSO-controlled system results in 27–32% of savings over the PI control. Maintenance cost also decreases by 15–18%, primarily due to lower degradation rate and enhanced thermal management. Further indirect economic benefits result from the decreased requirement for large hydrogen storage systems and hence the reduced vessel deadweight, allowing additional space to become available for cargo or passenger rooms. When extrapolated over the 25-year life of a typical vessel, these cumulative savings in fuel costs are estimated at greater than USD $1.3–$1.8 million, depending upon class and mission frequency of vessels thereby ensuring commercial marine adoption feasibility for the proposed control strategy.

In addition, in all the simulation domains such as efficiency, emissions, degradation, robustness, thermal management and cost analysis it is revealed that MOPSO-based framework has outperformed PI-, MPC-, SO-PSO-controller unequivocally. Both load-based and across-the-board efficiency improvements of 10–20% are maintained, with emission reductions in the range of 25–40% achieved as a result of improved operating trajectories and lower fuel consumption. Lifetime of the stack is greatly enhanced since degradation can be decreased by nearly 60%. Hydrogen consumption is reduced by ~23%, and a 74% reduction in DC-link ripple can be achieved with significant improvement of power quality and propulsion smoothness. Tolerance to uncertainty increases from 3-6, and the economic case for deployment is strong as there are significant savings in cost for multi-mission marine vessels. These findings as a whole show that multi-objective optimization is the key to advancing hydrogen–fuel cell propulsion for future ships and MOPSO is an efficient methodology towards enabling sustainable, reliable and economically feasible maritime transport.

IV. CONCLUSIONS AND FUTURE WORK

This paper developed an overall optimization approach to enhance efficiency, energy utilization, and emissions performance in Hydrogen–Fuel Cell (HFC) based power systems for sustainable maritime using Multi-Objective Particle Swarm Optimization (MOPSO) technique. Results show that the HFC as a propulsion system would be a promising decarbonized merchant ship, which can contribute to substantial reduction in greenhouse gas emission and improved fuel efficiency while meeting growing stringent environmental regulations imposed on shipping industry thanks to advanced multi-objective algorithms. By enabling key objectives—fuel cell efficiency, hydrogen consumption, system thermal stability and NOx/particulate emissions—to be optimized simultaneously in the proposed MOPSO framework Pareto optimal solutions are able to be found that traditional single objective or rule-based methods cannot. The optimization results demonstrate large improvements of the system response, a less reduction in the lifetime yield, a superior load following capability and less fuel penalty for dynamic marine operation conditions (wave-induced loads,, varying propulsion power demands, ripple control).

The research also illustrates the significance of incorporating the system-level constraints (membrane hydration limit, stack temperature threshold and H2 storage pressure etc.) into the optimization to guarantee a real marine deployment. The generated Pareto fronts demonstrate that there are clear trade-off relationships between high-efficiency operation and low-emission modes, providing ship designers as well as operators the freedom to customize energy management profiles for mission-specific needs. The achieved enhancements of the measured performance further substantiate HFC technologies as an increasingly valuable building block for future low carbon and zero-emission marine propulsion systems.

In the future work, we try to generalise the optimisation framework by adding:

1) real-time and adaptive MOPSO targeting onboard applications at uncertainty;
2) hybrid energy systems, interconnecting fuel cell and storage devices including batteries, supercapacitors, or renewables (for example wind assisted propulsion);
3) analysis of lifecycle emissions that considers the various pathways in hydrogen production;
4) degradation conscious optimization formulations that account for long-term (stack) ageing, and so on.
5) hardware-in-the-loop or sea trial verification for enhancing practicality.

Such extensions will continue to push hydrogen–fuel cell integration towards complete autonomy, cost-effectiveness and environmental quality of marine vessels.

REFERENCES

1. Zhe Xiong, Yupeng Yuan, Liang Tong, Xiao Li, Boyang Shen, "Dynamic performance analysis of proton exchange membrane fuel cell in marine applications," Energy, Volume 310, 2024, 133218, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2024.133218.
2. Elkafas, Ahmed G., Massimo Rivarolo, Eleonora Gadducci, Loredana Magistri, and Aristide F. Massardo. 2023. "Fuel Cell Systems for Maritime: A Review of Research Development, Commercial Products, Applications, and Perspectives" Processes 11, no. 1: 97. https://doi.org/10.3390/pr11010097
3. Kai Meng, Haoran Zhou, Ben Chen, Zhengkai Tu, "Dynamic current cycles effect on the degradation characteristic of a H2/O2 proton exchange membrane fuel cell, " Energy, Volume 224, 2021, 120168, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2021.120168.
4. Di Micco, Simona, Filippo Scamardella, Marco Altosole, Ivan Arsie, and Mariagiovanna Minutillo. 2025. "Advancing Sustainable Propulsion Solutions for Maritime Applications: Numerical and Experimental Assessments of a Methanol HT-PEMFC System" Energies 18, no. 19: 5119. https://doi.org/10.3390/en18195119
5. San Martín, Idoia, Alfredo Ursúa, and Pablo Sanchis. 2014. "Modelling of PEM Fuel Cell Performance: Steady-State and Dynamic Experimental Validation" Energies 7, no. 2: 670-700. https://doi.org/10.3390/en7020670
6. Cem Ünlübayir, Hiba Youssfi, Rehan Ahmad Khan, Santiago Salas Ventura, Daniele Fortunati, Jonas Rinner, Martin Florian Börner, Katharina Lilith Quade, Florian Ringbeck, Dirk Uwe Sauer, "Comparative analysis and test bench validation of energy management methods for a hybrid marine propulsion system powered by batteries and solid oxide fuel cells, Applied Energy, Volume 376, Part A, 2024, 124183, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2024.124183.
7. Xing, Hui, Charles Stuart, Stephen Spence, and Hua Chen. 2021. "Fuel Cell Power Systems for Maritime Applications: Progress and Perspectives" Sustainability 13, no. 3: 1213. https://doi.org/10.3390/su13031213
8. Liu, Huanbo, Yi Guo, Yayu Yang, and Bing Han. 2025. "An IPSO-RC-Based Study on Dynamic Coordination Excitation and Optimal Capacity Allocation for Marine Hybrid Energy Systems" Journal of Marine Science and Engineering 13, no. 11: 2197. https://doi.org/10.3390/jmse13112197
9. Birkner, L., Foreta, M., Rinaldi, A. et al. Dynamic accelerated stress test and coupled on-line analysis

program to elucidate aging processes in proton exchange membrane fuel cells. Sci Rep **14**, 3999 (2024). https://doi.org/10.1038/s41598-024-54258-8

10. Qasem, Naef A. A., Abdulrahman, Gubran A. Q., A Recent Comprehensive Review of Fuel Cells: History, Types, and Applications, International Journal of Energy Research, 2024, 7271748, 36 pages, 2024. **https://doi.org/10.1155/2024/7271748**
11. M.S. Reza, I.M.R. Fattah, Junkai Wang, M.A. Hannan, B.S. Zainal, Hwai Chyuan Ong, T.M.I. Mahlia, "Hydrogen-based hybrid energy system: A review of technologies, optimization approaches, objectives, constraints, applications, and outstanding issues," Renewable and Sustainable Energy Reviews, Volume 226, Part A, 2026, 116192, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2025.116192.
12. Khan, Aqib, Mathieu Bressel, Arnaud Davigny, Dhaker Abbes, and Belkacem Ould Bouamama. 2025. "Comprehensive Review of Hybrid Energy Systems: Challenges, Applications, and Optimization Strategies" Energies 18, no. 10: 2612. https://doi.org/10.3390/en18102612
13. Muhammad Maaruf, Aminu Babangida, Ijaz Ahmed, Muhammad Khalid, Péter Tamás Szemes, "Advanced control strategies for fuel cell hybrid electric vehicles — A review," Energy Conversion and Management: X, Volume 28, 2025, 101354, ISSN 2590-1745, https://doi.org/10.1016/j.ecmx.2025.101354.
14. Gouda, Nadia, and Hamed Aly. 2025. "Energy Management of Hybrid Energy System Considering a Demand-Side Management Strategy and Hydrogen Storage System" Energies 18, no. 21: 5759. https://doi.org/10.3390/en18215759
15. Adeyinka, A.M., Esan, O.C., Ijaola, A.O. et al. Advancements in hybrid energy storage systems for enhancing renewable energy-to-grid integration. Sustainable Energy res. **11**, 26 (2024). https://doi.org/10.1186/s40807-024-00120-4
16. Albert H. Schrotenboer, Arjen A.T. Veenstra, Michiel A.J. uit het Broek, Evrim Ursavas, "A Green Hydrogen Energy System: Optimal control strategies for integrated hydrogen storage and power generation with wind energy," Renewable and Sustainable Energy Reviews, Volume 168, 2022, 112744, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2022.112744.
17. Feng, Guoyu, Zhishu Feng, Peng Sun, Lulu Guo, and Zhiyong Chen. 2025. "A Overview of Energy Management Strategies for Hybrid Power Systems" Energies 18, no. 17: 4769. https://doi.org/10.3390/en18174769
18. Rekioua, D., Mezzai, N., Mokrani, Z. et al. Effective optimal control of a wind turbine system with hybrid energy storage and hybrid MPPT approach. Sci Rep **14**, 30013 (2024). https://doi.org/10.1038/s41598-024-78847-9
19. Lee Wai Chong, Yee Wan Wong, Rajprasad Kumar Rajkumar, Rajpartiban Kumar Rajkumar, Dino Isa, "Hybrid energy storage systems and control strategies for stand-alone renewable energy power systems," Renewable and Sustainable Energy Reviews, Volume 66, 2016, Pages 174-189, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2016.07.059.
20. Ogarek, Przemysław, Michał Wojtoń, and Daniel Słyś. 2023. "Hydrogen as a Renewable Energy Carrier in a Hybrid Configuration of Distributed Energy Systems: Bibliometric Mapping of Current Knowledge and Strategies" Energies 16, no. 14: 5495. https://doi.org/10.3390/en16145495
21. Ali, E.S., Elkholy, M.H., Senjyu, T. et al. A flexible multi-agent system for managing demand and variability in hybrid energy systems for rural communities. Sci Rep **15**, 16255 (2025). https://doi.org/10.1038/s41598-025-01288-5
22. Das, Deboleena, Chakraborty, Ishan, Bohre, AashishKumar, Kumar, Prince, Agarwala, Raja, Sustainable Integration of Green Hydrogen in Renewable Energy Systems for Residential and EV Applications, International Journal of Energy Research, 2024, 8258624, 20 pages, 2024. **https://doi.org/10.1155/2024/8258624**
23. Li, Jianlin, Ce Liang, and Zelin Shi. 2024. "A Coordinated Control Strategy for Efficiency Improvement of Multistack Fuel Cell Systems in Electric–Hydrogen Hybrid Energy Storage System" Batteries 10, no. 9: 331. https://doi.org/10.3390/batteries10090331
24. Ravikumar Jayabal, "Hydrogen energy storage in maritime operations: A pathway to decarbonization and sustainability," International Journal of Hydrogen Energy, Volume 109, 2025, Pages 1133-1144, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2025.02.207.
25. Ning, Min, Yuanxin Yao, Yuechen Zhan, Feng Pan, Yongjie Fu, Daoyi Chen, Mucong Zi, and Mengran Shi. 2025. "Hydrogen Production from Marine Renewable Energy: A Review" Energies 18, no. 24: 6490. https://doi.org/10.3390/en18246490
26. Ayhan Atiz, Mustafa Erden, Hatice Karakilcik, Mehmet Karakilcik, "Integrating renewable energy technologies in green ships for mobile hydrogen, electricity, and freshwater generation," International

Journal of Hydrogen Energy, Volume 89, 2024, Pages 1368-1382, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2024.09.302.

27. Haris Ishaq, Ibrahim Dincer, Curran Crawford, "A review on hydrogen production and utilization: Challenges and opportunities," International Journal of Hydrogen Energy, Volume 47, Issue 62, 2022, Pages 26238-26264, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2021.11.149.
28. Fan, Hongjun, Peggy Shu-Ling Chen, Andrew Harris, Nagi Abdussamie, Evan Mac A. Gray, Irene Penesis, and Javad A. Mehr. 2025. "Preliminary Feasibility Study of Using Hydrogen as a Fuel for an Aquaculture Vessel in Tasmania, Australia" Journal of Marine Science and Engineering 13, no. 11: 2037. https://doi.org/10.3390/jmse13112037
29. G. Di Ilio, A. Bionda, R. Ponzini, F. Salvadore, V. Cigolotti, M. Minutillo, C. Georgopoulou, K. Mahos, "Towards the design of a hydrogen-powered ferry for cleaner passenger transport," International Journal of Hydrogen Energy, Volume 95, 2024, Pages 1261-1273, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2024.08.434.
30. Pompodakis, Evangelos E., Georgios I. Orfanoudakis, Yiannis A. Katsigiannis, and Emmanuel S. Karapidakis. 2024. "Hydrogen Production from Wave Power Farms to Refuel Hydrogen-Powered Ships in the Mediterranean Sea" Hydrogen 5, no. 3: 494-518. https://doi.org/10.3390/hydrogen5030028
31. D. Liu, S. Case, "Durability study of proton exchange membrane fuel cells under dynamic testing conditions with cyclic current profile," Journal of Power Sources, Volume 162, Issue 1, 2006, Pages 521-531, ISSN 0378-7753, https://doi.org/10.1016/j.jpowsour.2006.07.007.
32. Choi, Youngjin, MyongHwan Kim, JiYoung Park, and Youngmo Goo. 2025. "Proton Exchange Membrane Fuel Cell Stack Durability Prediction Using Arrhenius-Based Accelerated Degradation Model" Applied Sciences 15, no. 3: 1300. https://doi.org/10.3390/app15031300
33. Larisa V. Karpenko-Jereb, Victor A. Kovtunenko, "Modeling of the impact of cycling operating conditions on durability of polymer electrolyte fuel cells and its sensitivity analysis," International Journal of Hydrogen Energy, Volume 48, Issue 41, 2023, Pages 15646-15656, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2023.01.029.
34. Wang, Dan, Haitao Min, Weiyi Sun, Bin Zeng, and Haiwen Wu. 2023. "Durability Study of Frequent Dry–Wet Cycle on Proton Exchange Membrane Fuel Cell" Energies 16, no. 11: 4284. https://doi.org/10.3390/en16114284
35. Ramírez-Cruzado, Andrea, Blanca Ramírez-Peña, Rosario Vélez-García, Alfredo Iranzo, and José Guerra. 2020. "Experimental Analysis of the Performance and Load Cycling of a Polymer Electrolyte Membrane Fuel Cell" Processes 8, no. 5: 608. https://doi.org/10.3390/pr8050608
36. Masih Mojarrad, Mehdi Zadeh, Kenneth Løvold Rødseth, "Techno-economic modeling of zero-emission marine transport with hydrogen fuel and superconducting propulsion system: Case study of a passenger ferry," International Journal of Hydrogen Energy, Volume 48, Issue 71, 2023, Pages 27427-27440, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2023.03.438.
37. Bayer, Muhammed Umar, Levent Bilgili, Sabri Alkan, Üstün Atak, and Veli Çelik. 2025. "Techno-Economic and Life-Cycle Assessment of Hydrogen–Ammonia Fuel Blends in Tugboat Engines for Sustainable Port Operations" Sustainability 17, no. 22: 10285. https://doi.org/10.3390/su172210285
38. Yujin Cheon, Hyunyong Lee, Kyung Hwan Ryu, Jinkwang Lee, "Techno-economic analysis of liquefied hydrogen and liquefied natural gas power systems for coastal vessels: Economic feasibility and critical parameters," International Journal of Hydrogen Energy, Volume 142, 2025, Pages 330-340, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2025.05.331.
39. Lei, Jinyong, Hang Zhang, Jun Pan, Yu Zhuo, Aijun Chen, Weize Chen, Zeyu Yang, Keying Feng, Lincai Li, Bowen Wang, and et al. 2024. "Techno-Economic Assessment of a Full-Chain Hydrogen Production by Offshore Wind Power" Energies 17, no. 11: 2447. https://doi.org/10.3390/en17112447
40. Panagiotis Karvounis, Gerasimos Theotokatos, Evangelos Boulougouris, "Environmental-economic sustainability of hydrogen and ammonia fuels for short sea shipping operations, International Journal of Hydrogen Energy, Volume 57, 2024, Pages 1070-1080, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2024.01.058.
41. Kansara, Sagar, Kourosh Rezanejad, Mohammad Jahanbakht, and Diogo M. F. Santos. 2025. "Evaluating Techno-Economic Feasibility of Green Hydrogen Production Integrated with a Wave Energy Converter Device" Fuels 6, no. 4: 92. https://doi.org/10.3390/fuels6040092
42. Davide Lanni, Gabriella Di Cicco, Mariagiovanna Minutillo, Viviana Cigolotti, Alessandra Perna, "Techno-economic assessment of a green liquid hydrogen supply chain for ship refueling," International Journal of Hydrogen Energy, Volume 97, 2025, Pages 104-116, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2024.11.410.
43. Nguyen, Huu-Linh, Sang-Min Lee, and Sangseok Yu. 2023. "A Comprehensive Review of

Degradation Prediction Methods for an Automotive Proton Exchange Membrane Fuel Cell" Energies 16, no. 12: 4772. https://doi.org/10.3390/en16124772

44. Foniok, Krystof, Lubomira Drozdova, Lukas Prokop, Filip Krupa, Pavel Kedron, and Vojtech Blazek. 2025. "Mechanisms and Modelling of Effects on the Degradation Processes of a Proton Exchange Membrane (PEM) Fuel Cell: A Comprehensive Review" Energies 18, no. 8: 2117. https://doi.org/10.3390/en18082117
45. Zhou, Mengfan, Steffen Frensch, Vincenzo Liso, Na Li, Simon Lennart Sahlin, Giovanni Cinti, and Samuel Simon Araya. 2022. "Modeling the Performance Degradation of a High-Temperature PEM Fuel Cell" Energies 15, no. 15: 5651. https://doi.org/10.3390/en15155651
46. Li, Shian, Jiakai Zhu, Guogang Yang, and Qiuwan Shen. 2025. "A Review on Impact of the Marine Salt Spray Environment on the Performance of Proton Exchange Membrane Fuel Cells" Journal of Marine Science and Engineering 13, no. 1: 172. https://doi.org/10.3390/jmse13010172
47. Annabel Broer, Henk Polinder, Lindert van Biert, “Polymer electrolyte membrane fuel cell degradation in ships — Review of degradation mechanisms and research gaps,” Journal of Power Sources, Volume 640, 2025, 236678, ISSN 0378-7753, https://doi.org/10.1016/j.jpowsour.2025.236678.
48. N. Shakeri, M. Zadeh and J. Bruinsma, "Dynamic Modeling and Validation of a Fuel Cell-Based Hybrid Power System for Zero-Emission Marine Propulsion: An Equivalent Circuit Model Approach," in IEEE Journal of Emerging and Selected Topics in Industrial Electronics, vol. 5, no. 3, pp. 1065-1079, July 2024, doi: 10.1109/JESTIE.2023.3288475.
49. Nazemian, A., Boulougouris, E., Aung, M.Z. (2025). Simulation of Hybrid Fuel Cell-Battery Propulsion System Scrutinizing Multi-scheme Energy Management for a CTV Boat. In: McNally, C., Carroll, P., Martinez-Pastor, B., Ghosh, B., Efthymiou, M., Valantasis-Kanellos, N. (eds) Transport Transitions: Advancing Sustainable and Inclusive Mobility. TRAconference 2024. Lecture Notes in Mobility. Springer, Cham. https://doi.org/10.1007/978-3-031-89444-2_62
50. M. Jamma, P. Bujlo and Ø. Ulleberg, "Control and Power Management of Battery-PEM Fuel Cell Hybrid Power System for Marine Propulsion Systems," 2023 IEEE International Conference on Energy Technologies for Future Grids (ETFG), Wollongong, Australia, 2023, pp. 1-6, doi: 10.1109/ETFG55873.2023.10407271.
51. L. Kwon et al., "Design and Implementation of Pure H2/O2 Fuel Cell–Battery Hybrid Systems for Long-Range AUVs," 2023 IEEE Vehicle Power and Propulsion Conference (VPPC), Milan, Italy, 2023, pp. 1-4, doi: 10.1109/VPPC60535.2023.10403296.
52. C. Ünlübayir, H. Youssfi, J. Rinner, S. Bihn, F. Ringbeck and D. U. Sauer, "Load Prediction of Ship Load Profiles for Hybrid Marine Energy Management Systems Using Neural Networks," 2024 IEEE Transportation Electrification Conference and Expo (ITEC), Chicago, IL, USA, 2024, pp. 1-6, doi: 10.1109/ITEC60657.2024.10598918.
53. A. Haxhiu, A. Abdelhakim, S. Kanerva and J. Bogen, "Electric Power Integration Schemes of the Hybrid Fuel Cells and Batteries-Fed Marine Vessels—An Overview," in IEEE Transactions on Transportation Electrification, vol. 8, no. 2, pp. 1885-1905, June 2022, doi: 10.1109/TTE.2021.3126100.