ISSN: 2710-0588

Fuel Cell Power Systems for Maritime Applications: Hybrid Architectures, Energy Management and Deployment Challenges

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Abstract

The decarbonization of maritime transport is accelerating the transition from conventional diesel-based propulsion to low- and zero-emission power systems. Fuel cells are increasingly regarded as a promising option for ferries, inland vessels, harbor craft, research vessels and other mission-defined ships because they convert chemical energy into electricity with high efficiency, low acoustic signatures and zero local carbon emissions when operated on hydrogen. Nevertheless, their deployment at sea remains constrained by slow transient response, stack degradation, hydrogen storage volume, safety requirements, cost and the availability of bunkering infrastructure. For these reasons, most practical fuel-cell ship concepts adopt hybrid configurations in which fuel cells are coupled with batteries, supercapacitors or diesel generators. This review summarizes recent progress in maritime fuel-cell power systems from four interrelated perspectives: fuel-cell technologies and shipboard architectures; hybridization and energy management; hydrogen storage, vessel integration and safety; and life-cycle emissions and commercialization barriers. Particular attention is paid to fuel-cell/battery systems, multi-stack power allocation, health-aware control and real-time energy management strategies. The review argues that future research should move beyond feasibility demonstrations and fuel-saving-oriented control toward integrated design frameworks that combine state-aware fuel-cell operation, degradation mitigation, mission-based sizing, safety-by-design and well-to-wake environmental assessment. Such an approach is essential for translating fuel-cell vessels from pilot projects into reliable and economically viable components of maritime decarbonization.

Keywords

Fuel cell ships; hydrogen; hybrid propulsion; energy management; PEMFC; battery storage; shipboard microgrid; maritime decarbonization.

1. Introduction

International shipping is under increasing pressure to reduce greenhouse gas emissions and local air pollutants. The 2023 IMO greenhouse-gas strategy strengthened the long-term ambition for international shipping and highlights the need for low- and zero-carbon fuels, innovative propulsion technologies and improved energy efficiency [1]. Emission inventories further indicate that shipping remains a non-negligible contributor to anthropogenic greenhouse-gas emissions, and that the scale of mitigation required cannot be achieved by operational optimization alone [2]. For this reason, alternative fuels, electric propulsion and hybrid power systems have become central topics in maritime engineering research [3-6].

Fuel cells are attractive in this context because they produce electricity electrochemically rather than through combustion. When hydrogen is used directly, the shipboard exhaust is limited mainly to water and heat, while nitrogen oxides, sulfur oxides and particulate emissions can be almost eliminated at the point of use. Compared with batteries, hydrogen fuel-cell systems can provide longer zero-emission operation for missions that exceed short duty cycles;

ISSN: 2710-0588

compared with conventional engines, they offer lower noise and vibration, which is beneficial for passenger comfort, harbor operations and oceanographic measurements. These advantages explain the growing interest in proton exchange membrane fuel cells, solid oxide fuel cells and related hybrid systems for marine applications [7-9].

The challenge is that the maritime environment imposes constraints that are less prominent in many land-based applications. Ship loads vary with propulsion demand, hotel load, sea state and mission equipment. The available space for fuel storage is limited, while redundancy and fail-safe operation are essential. Fuel-cell stacks are also sensitive to operating temperature, pressure, humidity, reactant supply and rapid load variations. If these factors are not managed properly, efficiency may decline and degradation may accelerate. Consequently, practical fuel-cell vessels generally rely on hybrid architectures in which fuel cells provide baseline or medium-frequency power, while batteries or supercapacitors buffer transients, stabilize the DC bus and improve system responsiveness.

This review focuses on fuel-cell power systems for ships rather than on alternative marine fuels in general. It synthesizes the literature on maritime fuel-cell technologies, vessel concepts, hybrid architectures, power allocation, real-time control, safety and life-cycle performance. The goal is to clarify the technical logic of the field: fuel cells are not simply a substitute for diesel engines; they require system-level co-design involving fuel storage, power electronics, energy storage, thermal management, safety engineering and mission-based energy scheduling.

2. Fuel Cell Technologies and Shipboard System Architectures

Several fuel-cell technologies have been considered for maritime use, but proton exchange membrane fuel cells and solid oxide fuel cells have received the most attention. PEMFCs operate at relatively low temperature, start quickly and have high power density, making them suitable for dynamic marine loads, ferries, small passenger vessels and auxiliary power systems. SOFCs operate at higher temperature and can achieve high electrical efficiency, especially when integrated with heat recovery or reforming of energy-dense fuels, but their slower start-up and thermal cycling limitations make them less suited to highly transient propulsion profiles [7-9]. The choice of fuel-cell type therefore depends not only on efficiency but also on duty cycle, fuel logistics, vessel space, heat integration and operational flexibility.

Hydrogen is the most direct fuel for PEMFC systems, whereas methanol, ammonia, liquefied natural gas and other carriers may require reforming or may be more appropriate for high-temperature fuel cells [10,11]. The engineering trade-off is particularly important at sea. Compressed hydrogen is technically mature but has limited volumetric energy density; liquid hydrogen offers higher storage density but requires cryogenic tanks, boil-off management and specialized bunkering infrastructure. For large ocean-going ships, the volume penalty of hydrogen remains a major obstacle, while for short-route or mission-defined vessels the storage problem is more tractable [10].

Fuel-cell vessel architectures can be grouped into all-fuel-cell systems, fuel-cell/battery hybrids, fuel-cell/supercapacitor hybrids and fuel-cell/diesel hybrids. All-fuel-cell systems are attractive for zero-emission operation, but they require sufficient fuel-cell capacity and hydrogen storage to cover the full mission. Hybrid systems are more common because they exploit the complementary characteristics of fuel cells and storage devices. The fuel cell supplies steady or slowly varying power, while the battery supports peak load, start-up, maneuvering and load fluctuations. Diesel-hybrid fuel-cell systems offer a transitional route for vessels requiring long endurance or operating in areas where hydrogen infrastructure is not yet reliable.

Design studies have shown how strongly the appropriate architecture depends on vessel mission. Comparative work on a coastal research vessel indicated that a hydrogen fuel-cell

ISSN: 2710-0588

hybrid could provide substantially longer zero-emission operation than a battery hybrid because the liquid-hydrogen/fuel-cell combination stores more usable energy per unit volume than the battery-only alternative for longer missions [13]. Earlier feasibility studies on hydrogen ferries and research vessels also demonstrated that technically viable designs are possible, provided that storage, safety, refueling and regulatory issues are addressed at the concept-design stage [14-16]. These studies are important because they shift the discussion from component efficiency to vessel-level feasibility.

Demonstration projects have provided additional evidence. The development of PEMFC-battery systems for tourist boats and small vessels has shown that fuel-cell modules can be integrated with lithium-ion batteries to supply propulsion and auxiliary loads [17,18]. Similar modeling and simulation studies for fuel-cell/battery boats have emphasized the need for power electronics and control strategies that can maintain voltage stability while satisfying propulsion demand [19]. However, most demonstrations remain at relatively modest power levels, and scaling toward high-power ships remains a separate engineering challenge involving modularization, cooling, ventilation and redundancy.

3. Hybridization, Energy Management and Degradation-Aware Control

Energy management is central to the performance of fuel-cell hybrid vessels. A poorly designed strategy may reduce the theoretical advantage of fuel cells by forcing them into inefficient or highly dynamic operating regions. The objectives of an energy management strategy generally include reducing hydrogen consumption, maintaining battery state of charge, stabilizing the DC bus, satisfying load demand, limiting fuel-cell ramp rates and extending stack life. These objectives are coupled, and optimizing one of them in isolation can degrade another.

Rule-based strategies, including frequency decoupling, state machines, proportional-integral rules and fuzzy control, are attractive because of their low computational burden and straightforward implementation. They are widely used in early-stage studies and experimental benches. Al Amerl et al. proposed a real-time control strategy for a fuel-cell/battery hybrid boat in which a frequency-based power-sharing method and converter-level current/voltage control are combined to stabilize the DC bus and reduce hydrogen consumption [20]. Such work is valuable because it connects high-level energy allocation with the physical response of DC/DC converters, rather than treating the power system as an idealized source.

Optimization-based strategies provide a more systematic framework. Equivalent consumption minimization, dynamic programming, model predictive control, particle swarm optimization and mixed-integer programming have all been investigated for fuel-cell hybrid ships [22-29]. Bassam et al. proposed improved and multi-scheme energy-management strategies for a fuel-cell/battery passenger vessel, showing that adaptive selection among operating modes can reduce energy consumption and component stress [22,23]. Rafiei Foroushani et al. examined a zero-emission ferry concept using fuel cells, batteries and shore charging, demonstrating the relevance of mission profiles and shore-side infrastructure to optimal scheduling [24].

Recent work has begun to address an important limitation of many earlier strategies: fuel-cell performance is not constant. Stack voltage, maximum power and efficiency change with temperature, pressure, aging and operating history. Cao et al. proposed a two-layer power-allocation method for fuel-cell ships in which an adaptive Kalman filter updates fuel-cell model parameters online and estimates the maximum power and maximum efficiency of each fuel-cell system [21]. The second layer then allocates power based on the state of charge of the battery and the real-time performance of individual fuel-cell modules. This is a significant step toward health-aware operation because it avoids imposing equal power on stacks with unequal performance.

ISSN: 2710-0588

Learning-based strategies are also attracting attention. Reinforcement learning can handle stochastic load profiles and continuous control actions, making it potentially suitable for ship propulsion systems operating under uncertain sea states and mission patterns [26]. However, learning-based control requires careful validation before shipboard use. Data coverage, safety constraints, interpretability and robustness under unseen operating conditions remain unresolved concerns. Hybrid approaches that combine physical constraints, model predictive control and learning-based prediction may offer a more credible route than purely data-driven policies.

A mature energy-management framework for fuel-cell ships should therefore be degradation-aware and multi-layered. The local control layer must regulate converters and the DC bus; the dispatch layer must coordinate fuel cells and storage devices; and the supervisory layer should incorporate mission prediction, weather information, component health and safety constraints. This hierarchy is particularly important for multi-stack systems, where independent stack control can improve efficiency and reduce uneven degradation.

4. Vessel Integration, Hydrogen Storage, Safety and Life-Cycle Performance

The engineering viability of fuel-cell vessels is not determined by the fuel-cell stack alone. Hydrogen storage, ventilation, thermal management, fire safety, hazardous-zone classification, electrical integration and refueling logistics all affect the feasibility of a design. Hydrogen has a wide flammability range and low ignition energy, but it also disperses rapidly when released. Ship design must therefore prevent accumulation in enclosed spaces through effective ventilation, continuous detection and automatic isolation. The relevant safety philosophy is not to eliminate risk by component selection alone, but to manage fuel release, ignition sources, compartment layout and emergency shutdown as an integrated system [33,34].

Storage choice is one of the most consequential design decisions. Compressed gaseous hydrogen is suitable for small vessels and short routes but requires large cylinder volume. Liquid hydrogen can extend zero-emission range but introduces cryogenic materials, insulation, boil-off handling and bunkering complexity. For mission-defined vessels, such as ferries, harbor craft and coastal research vessels, liquid hydrogen can be justified when zero-emission endurance is a strong design driver [13-16]. For ocean-going cargo ships, hydrogen storage volume remains a major limitation unless ship design, route planning and refueling networks evolve together.

Fuel cells also interact with shipboard thermal and electrical systems. PEMFC systems require cooling, humidification and reactant supply control, while SOFC systems may offer heat-recovery opportunities but impose high-temperature integration constraints. Power electronics must isolate sources, regulate the DC bus and prevent reverse power flow into sensitive components. Battery packs add their own thermal and safety requirements. These subsystems occupy space, add mass and introduce maintenance needs. Therefore, a fuel-cell vessel should be designed as an integrated shipboard microgrid rather than as a conventional vessel with a fuel-cell generator inserted in place of a diesel generator.

Life-cycle assessment is essential for evaluating the environmental benefit of fuel-cell ships. A hydrogen fuel-cell vessel may have zero local carbon emissions, but well-to-wake emissions depend on how hydrogen is produced, compressed or liquefied, transported and bunkered. Renewable electrolysis hydrogen can deliver substantial greenhouse-gas reductions; fossil-derived hydrogen without carbon capture can significantly reduce local pollution but may not provide deep climate benefits. Life-cycle studies therefore caution against equating zero exhaust emissions with zero climate impact [6,32]. The same logic applies to batteries: emissions depend on electricity generation, battery production and replacement cycles.

ISSN: 2710-0588

Cost remains a barrier. Fuel-cell stacks, hydrogen storage systems, safety equipment, power converters and bespoke vessel integration increase capital expenditure. Hydrogen fuel costs and bunkering availability also remain uncertain. Demonstration vessels are therefore most likely to emerge where environmental requirements, route predictability and public funding align. Nonetheless, early deployments provide operational data that are indispensable for improving reliability, reducing cost and developing safety standards.

5. Challenges and Future Perspectives

Despite rapid progress, several issues still limit the commercial deployment of maritime fuel cells. First, fuel-cell durability under marine conditions is insufficiently documented. Salt-laden air, vibration, humidity, load cycling and extended service periods may accelerate degradation. Most published energy-management studies emphasize hydrogen consumption, while fewer explicitly include degradation cost, remaining useful life or uneven aging of multi-stack systems. Future control strategies should treat stack health as a state variable rather than as an afterthought.

Second, the coupling between energy management and vessel operation remains underdeveloped. Ship speed, route, weather, hotel load and mission equipment all influence the power profile. Energy management should therefore be linked with voyage planning, speed optimization and predictive load forecasting. For ferries and research vessels, repeated mission patterns can be exploited; for harbor craft, real operating data can inform predictive controllers; for offshore support vessels, stochastic load models may be required.

Third, hydrogen infrastructure is a limiting factor. Fixed-route ferries and inland vessels can be paired with dedicated bunkering stations, but larger and less predictable vessels require wider fuel availability. Green hydrogen supply, liquefaction capacity, port storage, bunkering standards and emergency response procedures must develop in parallel with shipboard systems. Without such infrastructure, technically feasible fuel-cell vessels will remain confined to pilots and niche applications.

Fourth, regulatory development must keep pace with engineering practice. Existing low-flashpoint fuel rules provide a foundation, but hydrogen-specific guidance is still evolving. Rules should address compressed and liquid hydrogen storage, fuel-cell spaces, ventilation, gas detection, shutdown philosophy, fire protection, bunkering and crew training. The absence of mature prescriptive rules can slow deployment, but overly rigid rules may also inhibit innovation. A goal-based framework supported by risk assessment, testing and operational feedback is likely to be most appropriate.

Fifth, research should move from isolated component studies toward integrated design optimization. Future fuel-cell vessels should be evaluated using a combined framework including mission-based sizing, dynamic simulation, safety analysis, life-cycle assessment and techno-economic evaluation. Such integration is necessary because a design that is optimal for hydrogen consumption may be unattractive in terms of storage volume, capital cost, safety zoning or lifecycle emissions.

Overall, fuel cells are unlikely to replace conventional marine engines uniformly across all ship types in the near term. Their strongest opportunities lie in vessels with predictable routes, moderate power demand, high local-emission sensitivity and access to low-carbon hydrogen. In these applications, fuel-cell/battery hybrid systems can deliver meaningful reductions in local pollution and, if supplied by renewable hydrogen, significant well-to-wake climate benefits. The next stage of research should prioritize health-aware energy management, standardized modular systems, validated safety designs and lifecycle-based decision tools. Only through this system-level approach can maritime fuel cells progress from promising demonstrations to robust and scalable power systems for low-carbon shipping.

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References

[1] International Maritime Organization. (2023). *2023 IMO Strategy on Reduction of GHG Emissions from Ships*. https://www.imo.org

[2] International Maritime Organization. (2020). *Fourth IMO Greenhouse Gas Study 2020*.

[3] DNV. (2023). *Maritime Forecast to 2050*.

[4] Bouman, E. A., Lindstad, E., Rialland, A. I., & Strømman, A. H. (2017). State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping. *Transportation Research Part D: Transport and Environment*, 52, 408–421. https://doi.org/10.1016/j.trd.2017.03.001

[5] Balcombe, P., Brierley, J., Lewis, C., Skatvedt, L., Speirs, J., Hawkes, A., & Staffell, I. (2019). How to decarbonise international shipping: Options for fuels, technologies and policies. *Energy Conversion and Management*, 182, 72–88. https://doi.org/10.1016/j.enconman.2018.12.013

[6] Gilbert, P., Walsh, C., Traut, M., Kesieme, U., Pazouki, K., & Murphy, A. (2018). Assessment of full life-cycle air emissions of alternative shipping fuels. *Journal of Cleaner Production*, 172, 855–866. https://doi.org/10.1016/j.jclepro.2017.10.165

[7] van Biert, L., Godjevac, M., Visser, K., & Aravind, P. V. (2016). A review of fuel cell systems for maritime applications. *Journal of Power Sources*, 327, 345–364. https://doi.org/10.1016/j.jpowsour.2016.07.076

[8] Xing, H., Stuart, C., Spence, S., & Chen, H. (2021). Fuel cell power systems for maritime applications: Progress and perspectives. *Sustainability*, 13(3), 1213. https://doi.org/10.3390/su13031213

[9] Elkafas, A. G., Rivarolo, M., Gadducci, E., Magistri, L., & Massardo, A. F. (2023). Fuel cell systems for maritime: A review of research development, commercial products, applications and perspectives. *Processes*, 11(1), 97. https://doi.org/10.3390/pr11010097

[10] McKinlay, C., Turnock, S. R., & Hudson, D. A. (2021). Route to zero emission shipping: Hydrogen, ammonia or methanol? *International Journal of Hydrogen Energy*, 46(55), 28282–28297. https://doi.org/10.1016/j.ijhydene.2021.06.085

[11] Osman, A. I., Nasr, M., Lichtfouse, E., Rooney, D. W., & Fennell, P. S. (2024). Hydrogen, ammonia and methanol for marine transportation. *Environmental Chemistry Letters*, 22(4), 2151–2158. https://doi.org/10.1007/s10311-024-01691-8

[12] de-Troya, J. J., Álvarez, C., Fernández-Garrido, C., & Carral, L. (2016). Analysing the possibilities of using fuel cells in ships. *International Journal of Hydrogen Energy*, 41(4), 2853–2866. https://doi.org/10.1016/j.ijhydene.2015.12.031

[13] Klebanoff, L. E., Caughlan, S. A. M., Madsen, R. T., Conard, C. J., Leach, T. S., & Appelgate, T. B. (2021). Comparative study of a hybrid research vessel utilizing batteries or hydrogen fuel cells. *International Journal of Hydrogen Energy*, 46(76), 38051–38072. https://doi.org/10.1016/j.ijhydene.2021.08.024

[14] Pratt, J. W., Klebanoff, L. E., Munoz-Ramos, K., Akhil, A. A., Curgus, D. B., & Schenkman, B. L. (2016). *Feasibility of the SF-BREEZE: A Zero-Emission, Hydrogen Fuel Cell, High-Speed Passenger Ferry*. Sandia National Laboratories.

[15] Pratt, J. W., & Klebanoff, L. E. (2018). *Optimization of Zero Emission Hydrogen Fuel Cell Ferry Design, With Comparisons to the SF-BREEZE*. Sandia National Laboratories.

[16] Klebanoff, L. E., Pratt, J. W., & LaFleur, C. (2018). *The Zero-V: Feasibility of a Liquid Hydrogen Fueled Coastal Research Vessel*. Sandia National Laboratories.

[17] Choi, C. H., Yu, S., Han, I. S., Kho, B. K., Kang, D. G., Lee, H. Y., Seo, M. S., Kong, J. W., Kim, G., Ahn, J. W., Park, S. K., Jang, D. W., Lee, J. H., & Kim, M. (2016). Development and demonstration of PEM fuel-cell-battery hybrid system for propulsion of tourist boat. *International Journal of Hydrogen Energy*, 41(5), 3591–3599. https://doi.org/10.1016/j.ijhydene.2015.12.163

[18] Shih, N. C., Weng, B. J., Lee, J. Y., & Hsiao, Y. C. (2014). Development of a 20 kW generic hybrid fuel cell power system for small ships and underwater vehicles. *International Journal of Hydrogen Energy*, 39(25), 13894–13901. https://doi.org/10.1016/j.ijhydene.2014.06.151

ISSN: 2710-0588

[19] Han, J., Charpentier, J. F., & Tang, T. (2014). An energy management system of a fuel cell/battery hybrid boat. *Energies*, 7(5), 2799–2820. https://doi.org/10.3390/en7052799

[20] Al Amerl, A., Oukkacha, I., Camara, M. B., & Dakyo, B. (2021). Real-time control strategy of fuel cell and battery system for electric hybrid boat application. *Sustainability*, 13(16), 8693. https://doi.org/10.3390/su13168693

[21] Cao, W., Geng, P., Xu, X., Guo, Y., & Ma, Z. (2023). A power allocation strategy for fuel cell ship considering fuel cell performance difference. *Scientific Reports*, 13(1), 9905. https://doi.org/10.1038/s41598-023-37114-3

[22] Bassam, A. M., Phillips, A. B., Turnock, S. R., & Wilson, P. A. (2016). An improved energy management strategy for a hybrid fuel cell/battery passenger vessel. *International Journal of Hydrogen Energy*, 41(47), 22453–22464. https://doi.org/10.1016/j.ijhydene.2016.09.099

[23] Bassam, A. M., Phillips, A. B., Turnock, S. R., & Wilson, P. A. (2017). Development of a multi-scheme energy management strategy for a hybrid fuel cell driven passenger ship. *International Journal of Hydrogen Energy*, 42(1), 623–635. https://doi.org/10.1016/j.ijhydene.2016.10.104

[24] Rafiei Foroushani, M., Boudjadar, J., & Khooban, M. H. (2021). Energy management of a zero-emission ferry boat with a fuel-cell-based hybrid energy system: Feasibility assessment. *IEEE Transactions on Industrial Electronics*, 68(2), 1739–1748. https://doi.org/10.1109/TIE.2020.2972453

[25] Wu, P., & Bucknall, R. (2020). Hybrid fuel cell and battery propulsion system modelling and multi-objective optimisation for a coastal ferry. *International Journal of Hydrogen Energy*, 45(4), 3193–3208. https://doi.org/10.1016/j.ijhydene.2019.11.172

[26] Wu, P., Partridge, J., & Bucknall, R. (2020). Cost-effective reinforcement learning energy management for plug-in hybrid fuel cell and battery ships. *Applied Energy*, 275, 115258. https://doi.org/10.1016/j.apenergy.2020.115258

[27] Peng, X., Chen, H., & Guan, C. (2023). Energy management optimization of fuel cell hybrid ship based on particle swarm optimization algorithm. *Energies*, 16(3), 1373. https://doi.org/10.3390/en16031373

[28] Ge, Y., Zhang, J., Zhou, K., Zhu, J., & Wang, Y. (2023). Research on energy management for ship hybrid power system based on adaptive equivalent consumption minimization strategy. *Journal of Marine Science and Engineering*, 11(7), 1271. https://doi.org/10.3390/jmse11071271

[29] Niu, L., Chen, H., Guan, C., & Zhang, Z. (2024). Optimization of topology and energy management in fuel cell cruise ship hybrid power systems. *Intelligent Marine Technology and Systems*, 2, 26. https://doi.org/10.35840/2692-8326/2426

[30] Xie, P., Asgharian, H., Guerrero, J. M., Vasquez, J. C., Araya, S. S., & Liso, V. (2024). A two-layer energy management system for a hybrid electrical passenger ship with multi-PEM fuel cell stack. *International Journal of Hydrogen Energy*, 50, 1005–1019. https://doi.org/10.1016/j.ijhydene.2023.10.238

[31] Liu, H., Fan, A., Li, Y., Bucknall, R., & Vladimir, N. (2025). Multi-objective hierarchical energy management strategy for fuel cell/battery hybrid power ships. *Applied Energy*, 379, 124981. https://doi.org/10.1016/j.apenergy.2024.124981

[32] Wang, H., Oguz, S., Jeong, M., & Zhou, X. (2023). Life cycle analysis of hydrogen powered marine vessels: Case ship comparison study with conventional power system. *Sustainability*, 15(17), 12946. https://doi.org/10.3390/su151712946

[33] American Bureau of Shipping. (2023). *Requirements for Hydrogen Fueled Vessels*.

[34] International Maritime Organization. (2015). *International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code)*.