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Durability and prognostic modelling of low-temperature polymer electrolyte membrane fuel cells in maritime applications: A review

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A B S T R A C T

Low-Temperature Polymer Electrolyte Membrane Fuel Cells (LT-PEMFCs) have recently emerged as a promising solution for sustainable ship energy systems. However, enhancing durability is essential to enable their broader adoption in the maritime sector. Durability enhancement depends on a thorough understanding of degradation mechanisms and accurate prognostics, both of which are highly application-specific. The current literature lacks a comprehensive understanding of LT-PEMFC degradation under maritime operating conditions and its integration into reliable prognostic models. To address this gap, this review provides an overview of LT-PEMFC durability and prognostic models from the perspective of maritime applications. Through a comparative analysis of studies across various sectors, we identify and discuss maritime-specific degradation drivers, including ship load profiles, sodium chloride contamination, vibrations, and wave-induced inclinations. Building on this analysis, we critically evaluate existing prognostic models and their suitability for lifetime prediction in maritime applications. This review proposes durability enhancement strategies based on current knowledge and highlights key research gaps requiring further investigation. In addition, it outlines promising prognostic methodologies and identifies technical challenges for application to maritime LT-PEMFCs. In this way, this work lays the foundation for enhancing LT-PEMFC durability in maritime environments and supporting its broader adoption for zero-emission ships.

1. Introduction

The shipping industry must reduce its environmental impact to comply with increasingly stringent regulations [1]. On a global scale, shipping is currently responsible for 3% of all anthropogenic greenhouse gas (GHG) emissions [2]. The International Maritime Organisation (IMO) aims for net-zero GHG emissions in international shipping by 2050 [3–5]. In addition, IMO has established stringent Emission Control Areas with strict nitrogen oxides (NO_x), sulphur oxides (SO_x), and particulate matter emission limits [3,4].

Until recent years, the cost of ownership had been the main driver for diesel engines and heavy fuels to become default choices for maritime power generation [6]. However, in light of stricter regulations and having reached a high degree of maturity in other mobility sectors, LT-PEMFCs have emerged as a promising alternative for sustainable ship energy systems [7,8]. Compared to internal combustion engines, LT-PEMFCs can achieve higher efficiency [7]. Moreover, they have advantageous technical characteristics, such as high specific power and power density, fast start-up time, and transient response. For these reasons, LT-PEMFCs have been the most applied technology in international research projects on fuel cell systems in maritime applications [9–11]. In line with the growing interest in the technology in the sector, several manufacturers have started producing LT-PEMFC stacks tailored for shipping applications in recent years. An overview of maritime LT-PEMFC technologies available on the market is provided in Table A.9. Moreover, IMO has released the first dedicated safety guidelines for ships using fuel cell power installations in 2022 [12].

Despite holding great potential for the maritime sector, the adoption of LT-PEMFC is still hindered by, among others, durability issues. Their performance degrades over time due to complex degradation mechanisms influenced by operating and environmental conditions [13]. Maritime applications are especially demanding in this regard, as most ships operate their power plants for extended periods in remote locations. As a result, LT-PEMFCs still lag behind conventional engines in safety, reliability, and cost-effectiveness.

Prognostics and Health Management (PHM) strategies have gained attention as a means to optimise LT-PEMFC performance and durability. By estimating the state-of-health and predicting the Remaining Useful Lifetime (RUL) of the system, PHM allows proper maintenance scheduling and development of strategies to enhance the system's

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lifetime [14]. However, developing effective prognostic models for maritime LT-PEMFCs requires a thorough understanding of their ageing mechanisms within the specific application context. The current LT-PEMFC prognostic models are primarily designed for different applications, leaving a gap in maritime-specific modelling approaches [15].

While several review papers have addressed the durability of LT-PEMFCs [13,16,17] and its prognostics [14,18–20] in recent years, these studies provide comprehensive insights into degradation mechanisms and lifetime estimation approaches under typical automotive operating conditions, such as standardised driving cycles, frequent start–stop cycles, and exposure to typical inland contaminants (e.g., SO_x, NO_x). In contrast, maritime applications introduce distinct operational conditions, such as variable ship load profiles, exposure to saline environments, and vessel-induced motions, that have not yet been systematically investigated and considered in prognostic models. While [21] reviewed degradation causes and mechanisms for maritime LT-PEMFCs, pointing out research gaps in the field, a comprehensive overview of durability enhancement strategies and prognostic models based on the understanding of degradation in maritime applications is still lacking. This review addresses this gap by coupling (i) a comprehensive overview of degradation factors and corresponding durability enhancement strategies for maritime LT-PEMFCs, and (ii) a critical assessment of existing prognostic models and their applicability to maritime LT-PEMFC systems. This work lays the groundwork for tackling durability challenges in maritime LT-PEMFC systems and for advancing prognostic models and durability enhancement strategies in line with progress in more mature sectors.

1.1. Structure and methodology

Section 2 presents the fundamentals of LT-PEMFC component functions and general degradation mechanisms. Section 3 identifies and analyses maritime degradation factors, including load demand, chemical contamination with particular attention to salt (NaCl) contamination, wave-induced inclinations, vibrations, and ambient temperature. Section 4 discusses degradation at the system level, points out potential durability enhancement strategies, and optimisation of materials and design. Finally, Section 5 introduces prognostic modelling approaches discussing their advantages and limitations, the utilised degradation datasets, and critically analyses the applicability of these models in a maritime context.

The literature search was conducted using Google Scholar and Scopus as primary databases. Keywords included ‘‘PEMFC’’, ‘‘durability’’, ‘‘prognostics’’, ‘‘degradation’’, ‘‘maritime fuel cells’’, and several keywords related to relevant degradation factors (load demand, air contamination, NaCl, vibrations, inclinations). The reference lists of the most relevant publications were screened to identify additional relevant studies. In addition to scientific databases, relevant reports and guidelines from maritime organisations, such as the IMO, as well as European and international maritime fuel cell research projects, were considered.

2. Degradation of components

LT-PEMFC durability is typically assessed based on performance degradation under specific operating and environmental conditions and is primarily linked to the chemical, mechanical, and thermal degradation of its components [22]. Degradation of individual components drives overall LT-PEMFC stack degradation, resulting in lower efficiency and reduced output power. Since this review targets a multidisciplinary audience, the purpose of this section is to briefly provide fundamental background on component structure, function, and generic degradation mechanisms that are well-known from automotive experience. This foundation ensures that readers less familiar with the technology can follow the subsequent discussion on the effects of maritime-specific degradation factors. In this regard, degradation mechanisms of each component have also been summarised in Table 1.

2.1. Electrolyte membrane

Structure and role. The membranes used in LT-PEMFC are ionomers, polymers modified to include ions, usually sulphonic groups, in their molecular structures [23]. Most membranes used are based on perfluorosulphonic acid (PFSA), such as Nafion [24]. It allows proton conduction from anode to cathode, while separating the oxidising and reducing environments on the cathode and anode sides, and provides support to the catalyst layers [25,26]. The membrane must have good thermal, chemical, and mechanical stability, high proton conductivity, and low permeability to gases [13,26].

Degradation mechanisms. Membrane degradation occurs through mechanical, thermal, and chemical mechanisms. Mechanical degradation includes cracks, tears, punctures, and pinholes caused by external particles introduced during Membrane Electrode Assembly (MEA) fabrication, as well as delamination at the membrane–electrode interface [25,27,28]. Pinholes and cracks result in hydrogen crossover, which can cause catastrophic safety issues and direct failure [13,29]. Changes in relative humidity can create mechanical stress cycles on the membrane. Operation at high relative humidity leads to membrane swelling, whereas low humidification causes the membrane to become brittle and fragile [30]. In addition, the formation of ice crystals within the membrane under sub-freezing temperatures can cause local ruptures and catastrophic mechanical failure [31].

Thermal degradation occurs at high-temperature operation, resulting in proton conductivity reduction [32–34]. The optimal temperature range for LT-PEMFC is between 60 °C and 80 °C. Above 80 °C (glass transition temperature), membranes are more susceptible to critical ruptures. Membrane stability is generally guaranteed up to 150 °C; at higher temperatures, the structure decomposes via its side sulphonate acid groups [13].

Chemical degradation is the most critical mechanism. In the cell's environment, the chemical interaction between hydrogen peroxide (H_2O_2) and iron ions (Fe^{2+} and Fe^{3+}) results in the formation of peroxide (•OH) and hydroperoxide (•HOO) radicals. These radicals attack the hydrogen-containing terminal bonds or the main chain of the PFSA structure, causing chemical decomposition, loss of mechanical strength, and reduction of proton conductivity [13,25,28]. Research investigations concluded that radicals produced by the decomposition of peroxide are the primary source of membrane failure [30,35]. The presence of trace amounts of Fe is known to be one of the leading causes of radical formation. However, even in the absence of Fe impurities, the Pt catalyst can also serve as a radical source [36]. The Pt catalyst is exposed to harsh oxidation conditions and becomes unstable at higher voltages in acidic environments, leading to dissolution and migration of particles into the membrane [37]. The contamination of foreign species, such as SOx, influences the oxygen reduction reaction, leading to the production of H_2O_2 [38]. Moreover, cation contamination (Fe, Cu, Ni) can take the place of protons in the sulphonic acid groups, causing dehydration and consequent proton conductivity reduction [39,40].

Degradation causes. Mechanical and thermal degradations are mainly due to high temperature and low relative humidity [41]. Shrinking and swelling from humidification variations lead to hydrothermal fatigue (mechanical degradation) when the membrane is constrained into the assembled cell [13]. Radical formation is accelerated under open circuit voltage or high potential and low relative humidity [13], and by the presence of metal ions like Fe^{3+} and Fe^{2+} that are mainly generated by corrosion of the end plates or of the piping system [28,42].

2.2. Electrodes

Structure and role. The electrodes are composed of a carbon support filled with platinum-based (Pt) catalyst nanoparticles, in an ionomer matrix (commonly Nafion) [41]. The carbon support ensures Pt particle dispersion (2–3 nm) and electronic conductivity, transports reactants and electrons to the Pt nanoparticles, and removes water and inert

Table 1
Summary of component degradation mechanisms, general causes and effects. The severity of each mechanism is classified in (i) light, for long-term stable degradation, (ii) severe, for irreversible degradation that strongly impacts lifetime but does not usually cause abrupt failure by itself, and (iii) destructive, for rapid degradation that potentially leads to component or stack failure.

Component	Mechanism	General causes	Effects	Severity
Membrane	Thermal degradation	High temperature; hydration/dehydration cycles	Side-chain/main-chain scission; conductivity loss	Severe
	Mechanical degradation	RH/temperature cycling; pressure differentials; extreme temperatures	Crack formation; pinholes; gas crossover	Destructive
	Chemical degradation	$^{\bullet}$OH/$^{\bullet}$OOH formation; H_2/O_2 crossover; metal-ion contaminants	Chemical decomposition; conductivity loss, pinholes	Destructive
Electrodes	Pt dissolution	High potential cycling; load transients; air contamination	ECSA loss; Pt migration/banding; ORR activity drop	Severe
	Ostwald ripening	Potential holds; elevated temperature; high RH	Particle growth/agglomeration; ECSA loss	Light
	Pt detachment	Support corrosion; mechanical stress	Inactive Pt; ECSA loss; porosity change	Severe
	Carbon corrosion	$E \gtrsim 0.9$ V; start–stop; fuel starvation; high RH/T	Support collapse; conductivity loss; catalyst layer thinning	Severe
	Ionomer degradation	Radical attack ($^{\bullet}$OH/$^{\bullet}$OOH); high potential cycling; hydration/dehydration cycles	Loss of sulphonic groups; conductivity loss; catalyst isolation	Severe
GDL	PTFE loss	Potential cycling; oxidation at high RH/temperature	Increased flooding; water-management issues	Light
	Carbon corrosion	High potentials; start–stop; O_2 exposure	Porosity loss; electrical resistance increase	Severe
	Mechanical compression	Assembly pressure; load cycling	Cracks; porosity reduction; mass-transport resistance increase	Severe
Bipolar Plate	Corrosion	Acidic environment; high potential; air contamination	Increased interfacial contact resistance; ion contamination	Severe
	Coating degradation	Potential cycling; mechanical stress; flow-field shear	Loss of protection; increased contact resistance; ion contamination	Severe
	Mechanical degradation	Coolant/oxidant flow; vibration	Flow field deformation; non-uniform reactant flows	Light

Severity legend: Light Severe Destructive.

gases [43]. The Pt particles provide sites for the electrochemical reactions to occur. The ionomer ensures the presence of hydrophilic regions within the hydrophobic structure, allowing proton conduction to catalyst sites [44,45].

Degradation mechanisms. Electrode degradation is divided between catalyst layer degradation, carbon support degradation, and ionomer degradation, resulting in a reduction of catalytic activity [43]. The most common parameter used to evaluate catalytic activity is the Electrochemical Surface Area (ECSA). Catalyst degradation occurs through several mechanisms: platinum dissolution under high potential cycling, followed by re-deposition in less active regions or migration into the membrane; particle growth and agglomeration (Ostwald ripening), where smaller particles dissolve and redeposit onto larger ones, decreasing the overall surface-to-volume ratio; and particle detachment, often caused by weakening of the support, rendering nanoparticles electrochemically inactive [13]. Carbon support corrosion happens when carbon becomes thermodynamically unstable under certain operating conditions that accelerate its electrochemical oxidation to CO_2 [46]. This corrosion weakens the support–catalyst interface, promoting further particle detachment and loss of active sites (ECSA reduction). Ionomer degradation can undergo chemical attack by radicals, leading to side-chain scission and loss of sulphonic acid groups, as explained in Section 2.1 [47]. Mechanical degradation due to hydration/dehydration cycles can further exacerbate ionomer degradation. Several works have pointed out that, regardless of the operation, the cathode is more affected by degradation [48]. The Pt catalyst is also strongly sensitive to several chemical contaminants that occupy its active sites, resulting in ECSA reduction.

Degradation causes. Electrode degradation mechanisms are enhanced by undesirable temperature and humidity, contaminants coming from fuel or oxidant flows, and load cycling [25,49]. Ostwald ripening is mainly caused by load cycling, combined with high temperature and low relative humidity [50]. The presence of chemical contaminants in the oxidant flow, such as SO_x, CO, NO_x, strongly affects catalyst degradation. Carbon corrosion is enhanced by fuel starvation under steady-state, by start-up and shutdown cycles, water flooding, idling, and by sub-freezing or excessively high temperatures [26,31,41,51]. Ionomer degradation is promoted by radical attack, under high potential cycling and elevated oxygen partial pressure, and is further accelerated by hydration–dehydration cycling that induces mechanical stress in the thin ionomer films [47].

2.3. Gas diffusion layer

Structure and role. The Gas Diffusion Layer (GDL) is a porous, electrically and thermally conductive structure made of two layers: a macro-porous substrate made of carbon fibres, and a microporous layer made of carbon powder and hydrophobic material (usually PTFE) [27,52]. It is sandwiched between the catalyst layer and the flow field, supporting and protecting the catalyst layer, conducting electrons, transporting chemical reactants, and removing the produced liquid water [27].

Degradation mechanisms. GDL degradation includes the increase in mass transport resistance, conductivity loss, and deterioration in water management capability [53]. The primary GDL degradation mechanism is carbon corrosion or oxidation, caused by the formation of water droplets during demanding operating conditions [54]. GDL carbon fibres can be oxidised by water, causing loss of hydrophobicity and porosity reduction. Moreover, PTFE can rearrange, thin, or partially detach from carbon fibres, and contaminants can foul the surface. Consequently, the gas transport resistance increases, and the cell efficiency reduces [52]. The resistance to mass transport can also be increased by a non-uniform assembly force that causes mechanical degradation, such as cracks or pore collapse.

Degradation causes. GDL degradation is enhanced by operating conditions such as start-up and shut-down, and abnormal conditions such as fuel starvation [54]. In particular, cyclic loading, high potentials, and high temperature and humidity can cause GDL porosity to decrease, deteriorating its transport capabilities [55]. Assembly pressure and load cycling have an impact on mechanical degradation.

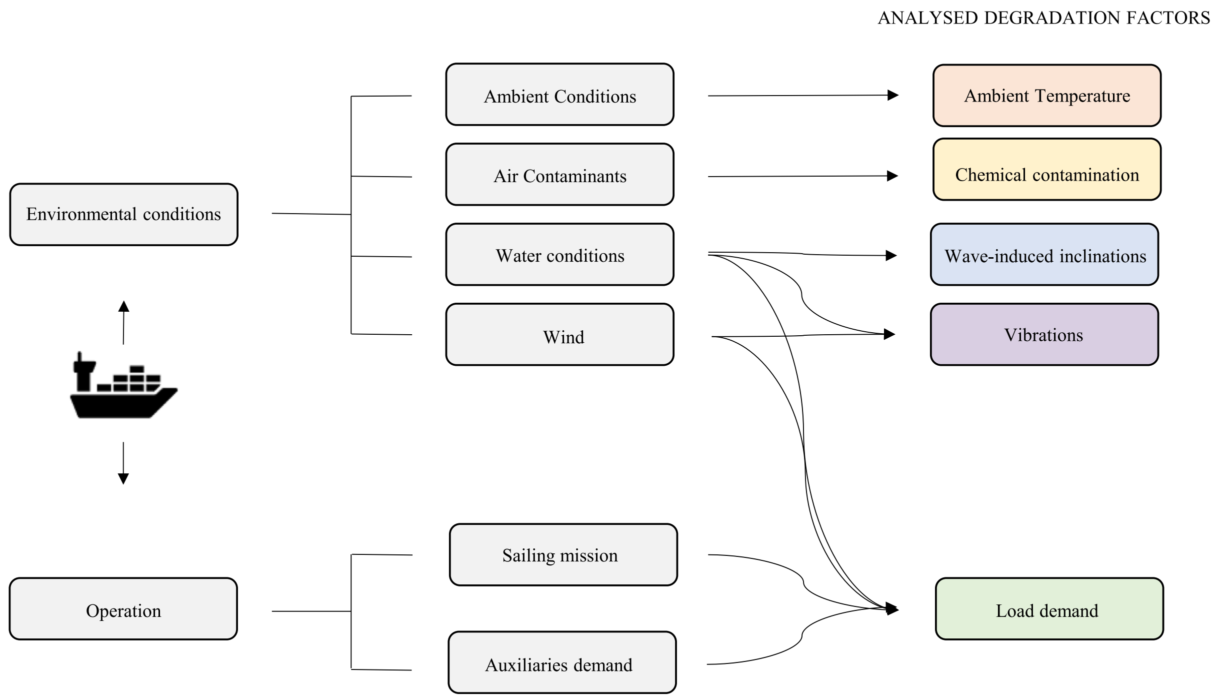

Fig. 1. Overview of the maritime-induced degradation factors analysed in this paper.

2.4. Bipolar plates

Structure and role. Bipolar plates are multi-functional components that act as a separator between fuel, oxidant gases, and coolant, distribute reactant and product streams, and collect the generated electric current [13]. Moreover, they have a sealing function for the cell, which is crucial for its safety and efficiency, by separating the reactant gases and coolant from each other as well as the external environment [56]. The most common materials for bipolar plates are graphite and graphite composites due to their lightweight, high corrosion resistance, and high electrical and thermal conductivity [57]. Metallic materials such as stainless steel, aluminium, nickel, and titanium are commonly used for bipolar plates as well [57]. Bipolar plate characteristics are high electrical and thermal conductivity, low gas permeability, high corrosion resistance, low cost, and good thermal and chemical stability [25].

Degradation mechanisms. Bipolar plate degradation mechanisms include corrosion, leading to the production of cations (Fe, Cu, Ni) that also impact membrane and catalyst durability; coating degradation, which increases the surface-layer ohmic resistance of the plates; and mechanical fractures or deformation [13,31,42]. Graphite-based plates corrode less than metal plates [13]. A reduction of their sealing capability can lead to coolant leakages and MEA contamination, resulting in drastic performance reductions and, eventually, system failure [58].

Degradation causes. Bipolar plate degradation is enhanced under extreme operating conditions, thermal cycles, non-uniform temperature distribution, air contamination, and by shocks or vibrations [59].

3. Maritime degradation factors

While the fundamental degradation mechanisms of each component described in Section 2 are mainly known from automotive research, their rate and severity are highly dependent on the application. Maritime LT-PEMFCs are exposed to operating conditions that can differ significantly from those of automotive systems and require tailored analysis. This section analyses the specific factors of maritime applications that impact LT-PEMFC degradation. An overview and classification of the analysed maritime degradation factors is provided in Fig. 1, while Table 6 summarises the most critical degradation mechanisms for each component and compares them with typical automotive mechanisms.

3.1. Load demand

3.1.1. Load-induced degradation

Load demand impacts cell lifetime due to various degradation mechanisms [60].

Generally, the most critical conditions are:

1. *Start and stop.* During system shutdown, ambient air can diffuse into the anode flow field through the anode exhaust channel. At start-up, hydrogen enters the anode and forms a hydrogen–air interface in the anode flow field, increasing the local potential at the cathode [61]. This condition increases catalyst and carbon support corrosion [62], and ionomer degradation [63].
2. *Idling.* Idling conditions cause high voltage operation, leading to carbon support corrosion, and increasing catalyst and electrolyte degradation [64,65]. It increases gas crossover, which can also cause local hot spots in the membrane [66].
3. *Open circuit voltage.* Open circuit voltage is an extreme condition that increases membrane chemical degradation, carbon corrosion, Pt catalyst dissolution, and agglomeration (Ostwald ripening) [63,66,67].
4. *High load.* High load causes extra-high current conditions, increasing the risk of gas starvation, water flooding, and local overheating [67–69]. Consequently, chemical degradation of the membrane is accelerated, as well as carbon corrosion, GDL corrosion, and Pt catalyst dissolution and agglomeration [60]. It can eventually cause flooding, during which liquid water accumulates in the catalyst layer and GDL pores, obstructing the flow of reactants and potentially leading to gas starvation.
5. *Dynamic load.* Load changing results in variations of water and heat generation, creating thermal and humidity cycles that accelerate catalyst and membrane ageing [70,71]. Parameter fluctuations during transients, such as stoichiometric ratio of supplied air and fuel, pressure, temperature, and relative humidity, further accelerate component degradation [16,60]. Gas starvation caused by load transients affects the physical and chemical structure of the catalyst [72].

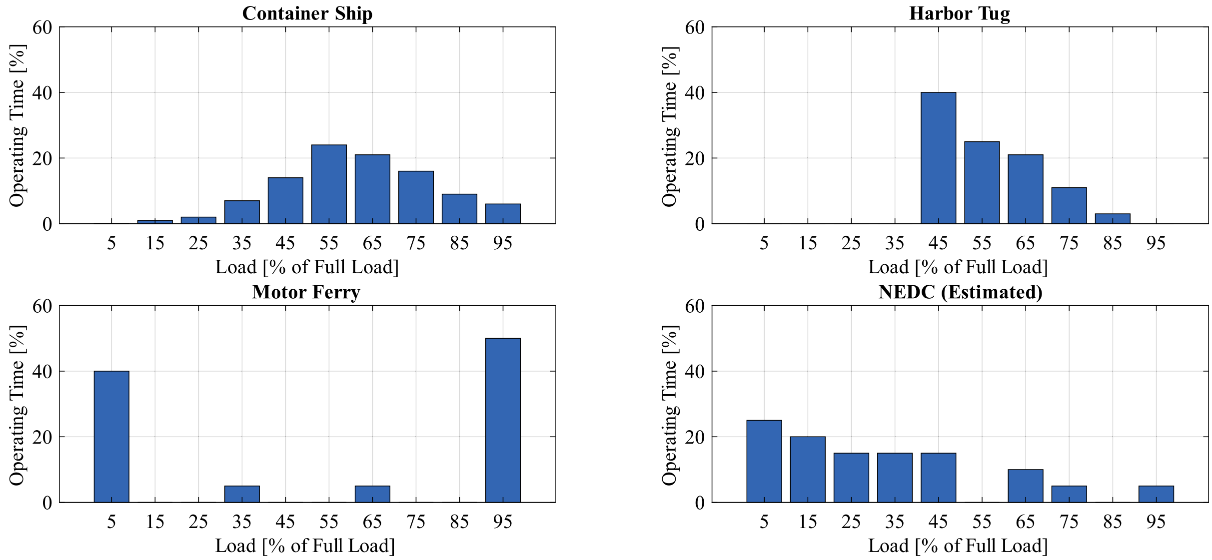

Fig. 2. Typical load distribution for a container ship, harbor tug, and motor ferry, elaborated from [75], compared to the estimated load distribution of the standardised New European Driving Cycle (NEDC). Load distributions are expressed in terms of percentage of rated power over percentage of operating time.

3.1.2. Automotive versus maritime load cycles

As the application of LT-PEMFC systems is relatively novel in the shipping sector, their ability to meet various vessel load demands and the associated durability effect require further investigation. Automotive research on load-profile-based degradation is more advanced, benefiting from standardised driving cycles that simplify operating conditions and serve as regulatory tools for performance evaluation [73]. Standardised cycles are also often employed to define LT-PEMFC durability testing [74]. In contrast, ships exhibit a vast range of load profiles depending on the application, and lack a similar standardisation of operating cycles.

Fig. 2 highlights the variation in load distribution across different vessel types, comparing typical load distributions of a post-panamax container ship, a harbour tug, and a motor ferry with the standardised New European Driving Cycle (NEDC) for automotive applications. While container ships exhibit more stable load distributions, smaller vessels, more suited for LT-PEMFC applications, generally experience higher load variability. This difference reflects the operational context: larger ships maintain relatively constant speeds over long ocean voyages, whereas smaller vessels frequently transition between high and low speeds in different operations, such as berthing or manoeuvring. These dynamic conditions can force LT-PEMFCs to operate in less favourable states, including idling or high-load operation.

Beyond mission type, a vessel's load profile is influenced by its sailing mission, operational conditions, and environmental factors. Unlike cars, ships experience substantial power fluctuations even at constant speeds due to external factors such as hull fouling, fuel and cargo variations, and manoeuvring conditions [76]. Additional load fluctuations caused by harsh maritime conditions include non-uniform wake effects, propeller cavitation, ventilation, and intense wave or wind conditions [77]. A typical vessel's power demand, even with thruster power management and speed control, can vary by up to 40% of nominal power within 10 s [75]. Such rapid fluctuations induce voltage drops that accelerate cell degradation, potentially leading to gas starvation and critical failure modes. Automotive studies indicate that 56.6% of LT-PEMFC performance degradation results from transient load fluctuations [78]. Given the even greater load variability of ships, direct power demands on LT-PEMFCs could further accelerate degradation.

Conversely, while start–stop cycles are frequent in automotive applications, they occur less often in maritime settings with longer sailing missions, potentially reducing their impact on LT-PEMFC durability. Once a ship reaches port, power is still needed for cargo operations and onboard hotel loads, minimising idling and open-circuit voltage conditions. However, extended operation without shutdown can contribute to degradation, as LT-PEMFCs often exhibit partial performance recovery after shutdowns due to reversible phenomena [79].

Table 2
LT-PEMFC voltage degradation rates measured by [80].

Operating conditions	Degradation rate	Unit
Start–stop	13.79	μV/cycle
Idling	8.662	μV/h
High power load	10.00	μV/h
Transient loading	0.4185	μV/cycle

Table 3
LT-PEMFC voltage degradation rates measured by Fletcher et al. [81,83]. RP = Rated Power.

Operating conditions	Degradation rate	Unit
Start–stop	23.91	μV/h
Low power load (0%–80% RP)	10.17	μV/h
High power load (> 80% RP)	11.74	μV/h
Transient loading	0.0441	μV/ΔkW

3.1.3. Quantifying load-induced degradation

In automotive research, several studies have attempted to quantify LT-PEMFC degradation by correlating voltage degradation rates with specific operating conditions. Chen et al. [80] derived voltage degradation from the operation of an LT-PEMFC bus operating in Beijing during the 2008 Olympic Games. The driving conditions were simulated as the sum of four typical operating conditions, reported in Table 2. Similar methodologies were applied by Fletcher et al. [81] and Staffell et al. [82]; their degradation coefficients are reported in Table 3. Some scholars have transferred these degradation rates to maritime LT-PEMFC applications. Wu et al. [83] use Fletcher's rates in their multi-objective optimisation study of a hybrid LT-PEMFC coastal ferry, while Dall'Armi et al. [84], Pivetta et al. [85], Balestra et al. [86], and Mylonopoulos et al. [87] incorporated these values in optimisation and energy management strategies. However, these degradation rates are derived from automotive powertrains operating under standardised driving cycles, which may not accurately reflect maritime LT-PEMFC/ESS systems.

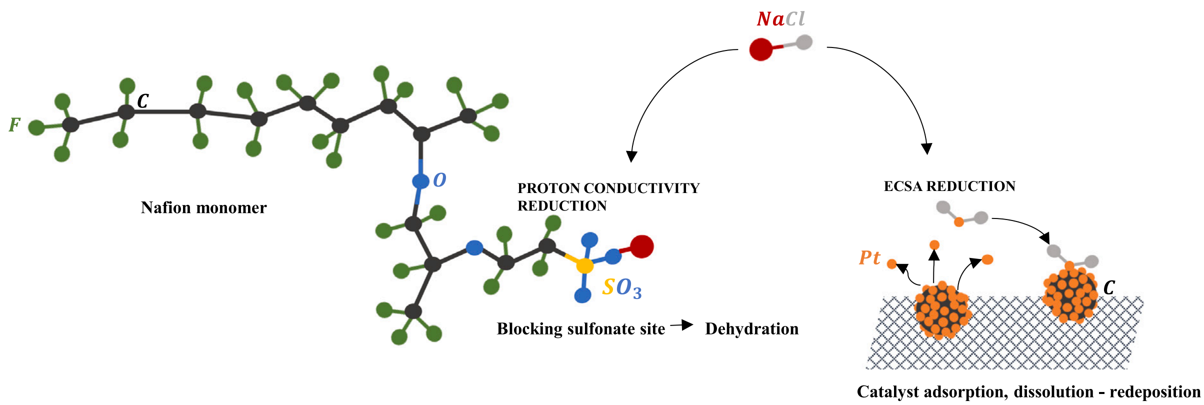

Fig. 3. Illustration of the observed NaCl degradation mechanisms for the electrolyte membrane polymer chain, by occupation of sulphonate sites, and for the catalyst, by particle adsorption, dissolution, and redeposition.

Most of the current studies focus on the effect of load demands in automotive driving cycles. Choi et al. [88] developed the first maritime durability protocol designed to mimic the operation of a small research vessel on an LT-PEMFC single cell over 300 operating hours. Their protocol resulted in more severe degradation compared to standard protocols for automotive and stationary applications, highlighting the need for further protocols to test the effect of various load profiles for different ship applications. This will also depend on the LT-PEMFC system topology and operating strategy, which may differ from those of typical automotive systems.

3.2. Chemical contamination

3.2.1. Fuel impurities

Fuel-side includes carbon monoxide (CO), ammonia (NH_3), and hydrogen sulphide (H_2S), and other sulphur–carbon based contaminants, primarily originating from the hydrogen production process [89,90]. To ensure high performance and longevity, LT-PEMFCs require high-purity hydrogen (≥99.97%). However, the filtration and separation processes necessary to remove these impurities are costly [91]. Thus, hydrogen production, purity, and cost are key factors in evaluating the techno-economic feasibility of LT-PEMFC maritime systems. If alternative hydrogen storage solutions, such as hydrogen carriers, will be adopted, their residuals and potential contamination effects will require further investigation [92].

3.2.2. General air contaminants

On the cathode side, air is the most practical and economical oxidiser for LT-PEMFCs [93]. However, ambient air contains various pollutants that can affect performance, and their composition varies by location [94]. Inland pollutants such as SO_x, NO_x, and carbon monoxide (CO) have been shown to degrade LT-PEMFC performance [95]. These same contaminants are also prevalent in harbour areas, making them relevant for marine applications. Among airborne contaminants, SO_x are the most detrimental and are particularly concerning in naval environments due to their proximity to marine diesel engines, gas turbines, and detonated explosives. SO_x adsorb onto the Pt catalyst, blocking oxygen from active sites and decreasing cell performance [96]. When SO_x contaminants reach the MEA, their pH decreases, resulting in free acid that could increase corrosion [93]. Additionally, SO_x can alter the oxygen reduction reaction, shifting it from a four-electron to a two-electron process, leading to hydrogen peroxide formation and subsequent radical-induced membrane degradation [38].

In the presence of Pt, NO absorbs to the cathode Pt particles, while NO_2 can either split into NO and oxygen or directly absorb on the catalyst surface area [103]. All these mechanisms result in ECSA decrease. CO can bind with the catalyst active sites, also resulting in ECSA decrease. The effect of CO is aggravated by low operational temperatures and high current density operation [93].

3.2.3. Salt contamination

Unlike automotive studies, where it is usually neglected, NaCl contamination is a significant concern in maritime LT-PEMFCs due to its high concentration in marine air [89]. Despite its significance, research on NaCl poisoning is still in its early stages. Mikkola et al. [97] found that injecting 1 ml/min of 1 M NaCl in the oxidant flow of a 25 cm^2 MEA caused an irrecoverable 33% performance loss over 100 h operating at 0.6 V. The study attributed this to the replacement of H^+ ions by Na^+ ions in the ionomer, reducing proton conductivity. Contrary to expectations, Cl^- ions did not significantly impact the MEA. However, NaCl absorbed into the graphite components, potentially acting as a long-term contamination source. The hypothesis on the effect of Na^+ ions was confirmed by Mahdav et al. [104], which investigated the effects of NaCl by ex-situ accelerated stress test on Nafion membranes based on Fenton's reagents. The authors proved that Na^+ ions can replace hydrogen in the carboxylic group of the membrane, reducing proton conductivity. Moreover, it was found that NaCl contamination accelerates radical formation from Fenton's reagents, accelerating the chemical degradation of the membrane.

Other studies investigated the effect of hydrochloric acid (HCl) contamination, providing further insights into degradation mechanisms associated with Cl^- ions. According to Matsouka et al. [105], Cl^- interacts with the catalyst layer, causing Pt dissolution and, consequently, a reduction of ECSA. Similarly, Li et al. [106] showed an increase in the size of Pt particles after HCl contamination.

The study of Sasank et al. [89] tested the effect of injecting a seawater mist at the cathode inlet of a stack consisting of 2 cells with 90 cm^2 active area, suggesting that ions from seawater could occupy electrode surfaces, hindering proton conductivity. They demonstrated that 87% of performance could be recovered by cathode washing with water, indicating that NaCl did not permanently poison the catalyst. However, the study did not specify the NaCl concentration causing the observed degradation.

Uemura et al. [98] operated a single cell (4 cm^2) under constant current density, with a poisoning flow rate of sea salt aerosol of 1.2 mg/h at the cathode side, and registered a cathode ECSA decrease of 22% after 50 min of contamination. Their results suggested that fine salt aerosol (1 μm particles) can reach the catalyst layer in the cathode by passing through the GDL, inducing performance degradation.

Park et al. [99] demonstrated that the poisoning mechanism varies depending on the operating voltage. When the LT-PEMFC is poisoned at the cell voltage of 0.6 V, the performance degradation is mainly due to the blocking of active sites by Cl^- ions adsorbed on the catalyst surface. At 0.9 V, the primary cause of performance degradation is instead the dissolution of Pt by Cl^-. Moreover, they assessed that applying 1.3 V to the cathode could recover 100% of the initial performance of the MEA poisoned at 0.6 V. This is because at lower voltages, the Cl^- ions adsorbed on the catalyst surface are the dominating poisoning

Table 4
Overview of experimental studies investigating the effect of NaCl contamination on LT-PEMFC performance.

Study	Flow ($g/h/cm^2$)	Duration (h)	Injection	Degradation	Recovery
Mikkola et al. [97]	1.4e−3	100	NaCl cathode injection	33% current density reduction at 0.6 V	Partial recovery by clean air feeding
Sasank et al. [89]	–	48	Sea water mist at cathode	60% power reduction	87% recovery by water washing
Uemura et al. [98]	3e−4	0.8	NaCl crystals injection at cathode	22.6% ECSA decrease	–
Park et al. [99]	5.8e−3	1	NaCl solution nebulised at cathode inlet	22% ECSA decrease at 0.6 V & 32% ECSA decrease at 0.9 V	100% recovery at 0.6 V and partial recovery at 0.9 by application of 1.3 V
Lamard et al. [100]	1.4e−2 &2.7e−5	0.5 & 165	NaCl mist injection at cathode inlet	Voltage drops	Partial recovery by cycles with pure water humidification and N_2 rinsing
Lamard et al. [101]	5.4e−4	10 & 43	NaCl mist injection at cathode inlet	Voltage drops	95% recovery by cycles with pure water humidification
Briand et al. [102]	1.09e−7	641	NaCl mist injection at cathode inlet	Crystals deposition at air inlet and GDL	–

mechanisms, and they can be oxidised and removed in the form of Cl_2 gas upon the application of a high voltage. On the other hand, the performance of the MEA poisoned at 0.9 V could not be fully recovered, indicating that irreversible dissolution of the Pt catalyst is the main cause of performance degradation in this case.

Lamard et al. [101] confirmed that NaCl contamination leads to performance loss and bipolar plates corrosion, and that NaCl can cross the GDL. A short-term (0.5 h) study was followed by a longer-term (up to 165 h) degradation test, highlighting that cells with metallic bipolar plates degraded eight times faster than those with graphite ones. Moreover, they proved performance recovery was possible through cathode washing for short contamination periods. However, after prolonged exposure, only partial recovery was observed, even at low NaCl concentrations.

Briand et al. [102] proved that lower, realistic concentrations of NaCl affect stack performance over long operating time (641 h). The authors found that at low concentration, the main affecting mechanism is deposition of NaCl crystals in the air inlet area and on the surface of the GDL, limiting the supply of air to the cathode. This significantly reduces the performance of the stack and can even lead to the shutdown of the cell.

To summarise, an overview of the above-mentioned experimental studies is given in Table 4, in which salt concentration has been normalised to allow comparisons between studies ($g/h/cm^2$) accounting for active area and testing time. Moreover, Fig. 3 illustrates the degradation mechanisms caused by NaCl affecting the electrolyte membrane and catalyst observed in the studies. These studies have proven that Na^+ causes membrane dehydration and reduces proton conductivity by occupying the sulphonate groups, while Cl^- affects the catalyst through adsorption, dissolution, and redeposition of Pt particles, ultimately leading to ECSA losses. In addition, ex-situ testing suggested that Na^+ ions can accelerate Fenton's reactions and radicals attack on the membrane, even though this mechanism has not been investigated and observed in any in-situ and in-operando test so far.

Degradation mechanisms were found to be affected by operating cell voltage, salt concentration, and exposure time. As summarised in Table 4, only a few studies exceeded 100 h of exposure [97,100,102], while the imposed NaCl concentrations vary widely across studies. Although it is common practice to accelerate stress tests by increasing the stressors, salt concentration should refer to realistic on-board conditions to yield meaningful conclusions. Reference values of actual NaCl concentration in sea air and onboard of vessels are scarce. To our knowledge, only [102] derived the test level from measured air concentrations (120 $\mu g/m^3$), which is within one order of magnitude of the MARANDA reference (10 $\mu g/m^3$) reported by Tallgren and Ihonen [107], making it a credible acceleration level. At this concentration, membrane and catalyst degradation were less impactful over the 641-hour test, whereas salt-crystal deposition in the air channel and on the GDL surface was the main cause of performance loss. Building on these observations, and given that most prior work used substantially higher NaCl concentrations, systematic studies with realistic concentrations and longer exposures are needed to further investigate the impact of degradation mechanisms and test the actual LT-PEMFC tolerance to sea air.

3.3. Wave-induced inclinations

The transport of multi-phase flows and water management are critical factors influencing the operational performance and durability of LT-PEMFCs. These challenges are exacerbated by typical marine motion loads, especially when ships operate in rough water conditions that can expose the LT-PEMFC to large inclinations and dynamic motions. Despite these challenges, very limited studies have focused on the effect of inclinations and multi-degree-of-freedom motions reflecting marine conditions.

Ejiri et al. [108] experimentally investigated the performance of an LT-PEMFC stack consisting of 15 single cells, exposed to 0°, 90°, and 180° static inclination. Their results showed that the stack could operate for more than 1 h only in the case of 90° inclination, while experiencing a temperature increase. Sudden power breakdowns occurred for both 0° and 180° inclination in less than 1 h of operation at 0.2 A/cm^2. According to the authors, the sudden power breakdown occurred due to a voltage drop in one of the downstream cells, likely caused by flooding in the anode. With 90° inclination, the LT-PEMFC stack was less likely to suffer from flooding because mass transfer was actively promoted in the cathode by natural convection in the vertical direction. Friedrich et al. [109] studied operation at a lower static 30° inclination at different stoichiometry supply for an aviation LT-PEMFC. The stack voltage dropped when air was supplied at low stoichiometry, and, similarly, the authors suggested water management issues as the primary cause of the performance reduction.

El-Emam et al. [110] studied the effect of different air flow rates (from 220 SLM to 660 SLM) and orientation (0°, 30°, 45°, and 90°) on a single cell with an active area of 25 cm^2. At low air flow rates, the performance showed little enhancement for cell orientation angles of −45° and 90°, but better enhancement at an orientation angle of −30°. By increasing the cell orientation angle, the gravity force leads to easy removal of the produced water, resulting in a dehydrated membrane at higher inclinations. At high air flow rates, in horizontal and nearly horizontal positions, cell efficiency and power density decreased. At the same time, at angles of −60° and 45°, they were slightly enhanced, and the best performance was achieved at an orientation angle of 90°. Here, instead, the air flowing against gravity helped to maintain a high hydration level in the membrane.

Yang et al. [111] investigated the influence of typical marine pitch and roll on the LT-PEMFC two-phase flow behaviour and electrochemical reactions, by a combined experimental and numerical approach. Their analysis revealed that marine motions induce inertial and viscous

Table 5
Summary of vibration test conditions of the analysed studies (frequency, amplitude) and observed effects.

Study	Frequency (Hz)	Amplitude (mm)	Effects
El-Emam et al. [110]	1.33, 2, 3	30–60	Low vibration enhances performance, high vibration reduces performance
Hou et al. [115]	random	–	Long-term vibrations reduce gas-tightness, increase ohmic and mass transport resistance
Wang et al. [116]	10, 20	3, 4	Voltage under/overshoots, performance drops in dynamic operation, steady-state performance increase under high vibration
Nan et al. [117]	200–2000	2, 4, 6	Voltage fluctuations and power drops up to 9%

forces, disrupting the uniformity of oxygen distribution and water drainage, particularly within the cathode flow field. These effects become increasingly pronounced at high current densities, where oxygen starvation and local flooding can severely impact cell performance. Pitch motion produced more significant performance degradation than roll, resulting in current density reductions of up to 3.05%. The study highlights how large-period, low-frequency marine motions can cause periodic non-uniform multiphase distributions, which in turn amplify polarisation losses and lower overall efficiency.

To summarise, the existing studies proved that marine motions impact the multiphase flows and water management in the cell, causing flooding, dehydration, and fuel starvation. In static tests, vertical orientation improved operability by aiding cathode drainage via natural convection [108]. At modest tilt (30°) and low air stoichiometry, stack voltage dropped, indicating water management limit [109]. Single-cell tests spanning from 0° to 90° show a regime shift with air flow rate: at low flow, larger inclination eases water removal but can dehydrate the membrane; at high flow, near-horizontal orientations penalise efficiency, while 45–90° perform best as flow against gravity helps retain adequate hydration [110]. Under dynamic marine motions, pitch and roll introduce periodic, non-uniform oxygen and water distributions that intensify at high current density, with pitch being more detrimental than roll. Even though the observed effects are reversible, causing temporary voltage drops that can be recovered by restoring the proper conditions, continuous exposure to such conditions can have a drastic impact on degradation. Continuous flooding conditions accelerate Pt degradation and carbon corrosion [46,112], while operating the cell with a dehydrated membrane can lead to pinholes and delamination in a relatively short time [113]. Therefore, performance tests over longer operating times are necessary to distinguish between reversible effects in the short run and long-term degradation effects.

3.4. Vibrations

Automotive-based experimental studies indicate that the performance of LT-PEMFCs is affected by road vibrations. The vibration environment experienced at sea is considerably more rigorous than that on land: according to ISO 20283-5:2016, the maximum load of a ship is 214 mm/s, which is much higher than the 4.6–144 m/s specified in IEC 61373:2011 for vehicle vibration [114]. However, there is currently no evidence on the effect of specific ship vibrations on LT-PEMFC coming from experimental studies.

To the best of our knowledge, [114] is the only model-based study investigating the effect of ship vibration on LT-PEMFCs. The computational fluid dynamics method investigates the internal mass transfer, hydrogen distribution within the cell, and the output voltage, assuming the vibration to be harmonic and referencing its intensity to IMO provisions. The study concluded that the gas transfer in the LT-PEMFC varies in the direction of the vibration, with vertical vibration having the most significant influence. The frequency and amplitude of vertical ship vibration enhance the effect of gas transfer of the LT-PEMFC, while the influence on the output voltage may be improved or weakened. The displacement amplitude was also shown to have a significant impact on cell performance. In contrast to the non-vibration case, the output voltages of the LT-PEMFC decrease by 7.9%, 0.48%, and 0.5% when the ship's vertical vibration is 1 Hz and 1.6 mm/s, 20 Hz and 1.6 mm/s, and 1 Hz and 1 mm/s, respectively, showing that the amplitude value of ship vibration has more influence on the LT-PEMFC.

Experimental evidence on the vibration effect mainly comes from automotive studies. El-Emam et al. [110] tested the effect of road-vibration on a single cell with 25 cm^2 of active area. They proved vibration effects depend on the air flow: at low cathode air flows (around 220 SLM), vibrations enhance the LT-PEMFC performance, but by increasing the cathode air flow, this positive effect decreases, and it is found to negatively affect the performance when the air cathode flow rate reaches 660 SLM. However, the duration of the experimental test is not reported, suggesting that the study aimed to investigate the real-time response of the LT-PEMFC under vibration, rather than its long-term degradation effect.

Hou et al. [115] investigated the durability influence of road-induced vibration on performance degradation of an LT-PEMFC stack for 250 h, finding that the gas-tightness of the stack degrades dramatically under long-term strengthened road vibration, causing an increase of 1.7 times in hydrogen leakage. The steady-state performance of the stack is significantly influenced by strengthened road vibration: the open circuit voltage and rated voltage decrease by 0.90% and 3.58%, respectively, and the ohmic resistance is found to increase linearly by 5.4%.

Wang et al. [116] tested dynamic response using both a standard and a transparent 25 cm^2 cell on a vibration platform, with varying amplitude (0, 3, 4 mm) and frequency (0, 10, 20 Hz). Under vibration, voltage transients exhibit larger under- and overshoots and longer settling times. However, a slight performance improvement is observed at 4 mm amplitude, attributed to the enhanced removal of excess water. Overall, they observed that amplitude and frequency modulate water management: they can both aggravate transient flooding (via droplet coalescence) and, in some regimes, accelerate drainage, explaining the mixed impact on voltage dynamics.

Nan et al. [117] developed a method to investigate the short-term effects of vibration on LT-PEMFC vehicles, finding that vibrations increase power fluctuations and cause a small drop in mean power of around 2% on average, with worst cases exceeding 9% under stronger excitation. Effects grow with acceleration level and current density. Moreover, cell orientation plays a crucial role, as it reduces power when the x-direction of the cell is aligned with the gravitational direction.

Most studies agree that harmonic excitations at low frequencies cause power fluctuations and can even increase output power, whereas high-frequency harmonic excitations tend to reduce output power. However, frequency alone does not dictate power loss or gain: amplitude and the prevailing water-management regime are critical, and high-frequency vibration can increase transient fluctuations yet leave steady-state power unchanged or slightly improved [115]. Table 5 reports the vibration frequencies and amplitudes applied in the analysed studies and summarises the observed effects. Currently, no studies have tested vibrations with amplitudes and frequencies specific to ships. Moreover, most studies focus on short-term effects of vibration, whereas long-term effects are mostly disregarded. Unlike inland transportation, ship components are more frequently exposed to continuous vibration excitations (propellers and waves are the primary sources), and reliability requirements are typically higher [118]. Vibration energy is continuously transmitted to onboard devices during

Table 6
Comparison of most relevant LT-PEMFC component degradation mechanisms in automotive and maritime applications.

Component	Typical automotive degradation	Additional/Distinctive maritime degradation
Electrodes	Pt dissolution/agglomeration under transient load cycling Active-site poisoning from CO, SO_x, NO_x Carbon corrosion during start–stop cycles	Cl^- blocks Pt active sites, promotes dissolution/redeposition Load fluctuations and pitch/roll motions → periodic flooding/dehydration, starvation
Membrane	Thermal/mechanical cycling from frequent start–stop and rapid load changes Radical attack enhanced by SO_x/NO_x in urban air Pinholes and crossover under dry/humid cycling	High load and transients → accelerated chemical/mechanical/thermal degradation Na^+ replaces H^+ in sulphonate groups; NaCl accelerates radical-driven polymer attack Risk of dehydration under inclinations
GDL	Hydrophobicity loss and compression under road vibrations Carbon oxidation/PTFE detachment during load cycling	Salt deposition blocks pores, reduces hydrophobicity Continuous ship vibrations and inclinations intensify mechanical degradation, carbon oxidation, PTFE detachment
Bipolar Plates	Corrosion of metallic plates under acidic environment Coating degradation under load cycling Moderate vibration/thermal cycling	Saline air accelerates corrosion Salt crystals deposit in flow channels → uneven reactant distribution Long-term vibrations/inclinations → sealing issues

ship operation and can accelerate cell degradation. Continuous mechanical stress is particularly critical for bipolar plates and sealing integrity [115]. Considering these observations, further studies are needed to test realistic shipboard frequency and amplitude ranges over long durations to assess LT-PEMFC performance and durability.

3.5. Ambient temperature

Exposing LT-PEMFCs to extreme temperatures can impact their durability. In particular, when subjected to sub-zero temperatures for an extended period, the residual water contained within the stack can freeze. This leads to thermal and mechanical stress, and hence to mechanical damage of the cell components, and may even cause physical breakdown [31]. Freezing water is particularly dangerous for MEA durability since it can cause catalyst layer delamination and electrolyte membrane cracks [119].

A primary concern at sub-zero temperatures is the start-up phase. If the generated water in the cathode is not removed while the cell is running at sub-zero temperatures, ice forms, causing a voltage drop and shutting down the electrochemical reaction [120]. Kunkel et al. [121] studied the effect of a low temperature range (0–20 °C) on the catalyst, finding decreasing activity with lower temperatures, but also significantly lower catalyst degradation rates due to lower kinetics. At 0 °C and lower stoichiometries (4 for air and 2 for H_2), a cold start attempt failed. A successful start-up was attained by doubling the stoichiometries of the flow rates.

Compared to automotive LT-PEMFCs, maritime LT-PEMFCs are less likely to be affected by the ambient temperature since they are normally located in engine rooms, where temperature control is possible both during ship operation and docking. Especially considering ships operating in regions with extreme ambient temperatures, the temperature control of the engine rooms is important for the operation and durability of maritime LT-PEMFCs.

4. Durability of maritime LT-PEMFC systems

4.1. Hybrid LT-PEMFC systems

Ship propulsion systems based on LT-PEMFCs typically present hybrid LT-PEMFC/Energy Storage Systems (ESS) powertrains [9]. Lithium-Ion Batteries (LIBs) are the most commonly applied ESS, while supercapacitors are recently gaining traction as an alternative ESS [122]. Fig. 4 shows the typical topology of a hybrid system. In these systems, the use of the main power generation system is generally optimised: the fuel cell stacks are responsible for providing the primary power output, while the ESS manages peak shaving and transient loads [123]. Furthermore, the ESS system allows for a lower LT-PEMFC installed power, reducing costs and storage requirements [124]. Hybrid LT-PEMFC/ESS systems typically present series architectures, where all power generators and their corresponding converters are connected to a main electrical grid. These systems typically feature bidirectional electric power flow between the electric bus and the ESS, allowing the ESS to be charged by the LT-PEMFC when the generated power exceeds the power demand.

The LT-PEMFC/ESS system for ships was first demonstrated on the FCS Alsterwasser vessel, the world's first hydrogen-fuelled passenger vessel, equipped with two LT-PEMFC systems of 48 kW each, and a 360 Ah/560 V lead gel battery [125]. Current hydrogen-powered ship projects typically install LT-PEMFC stacks in the range of 100 kW to 1.2 MW, with some planned concepts reaching up to 3 MW. Meanwhile, their ESS spans from 90 kWh to 2.5 MWh, depending on vessel size and operational profile. Further details on ongoing hydrogen-powered vessel projects and installed LT-PEMFC/ESS systems can be found in [9,126].

4.2. System-level durability

Durability is a key requirement for LT-PEMFC/ESS systems in maritime applications, where stringent safety and reliability standards need to be met. Ship energy system performance is typically evaluated under calm water conditions under current legislation [76], while off-design scenarios such as rough water conditions are accounted for by including a sea margin of about 15–25% [77]. Hybrid LT-PEMFC/ESS systems are thus sized to ensure that the fuel cell stacks can sustain a minimum guaranteed load under variable operating conditions. However, if LT-PEMFC degradation accelerates during vessel operation, the system's maximum deliverable power may decline faster than anticipated. Performance degradation shortens lifetime and necessitates accurate prediction to enable effective maintenance scheduling and the adoption of mitigation strategies.

To effectively assess system-level durability, it is essential to bridge the gap between individual component degradation mechanisms and the resulting performance decline at the stack and system level. While degradation studies typically isolate the effect of different degradation drivers, these factors are usually combined in real systems, accelerating degradation. For instance, NaCl contamination can further intensify radical attack on the membrane. Vibrations and wave-induced inclinations act simultaneously, potentially exacerbating water management issues triggered by load transients. Continuous exposure to such multi-stressor environments will result in non-linear, accelerated degradation at the stack level.

When scaling up from single cells to commercial-size stacks, inconsistency resulting from uneven ageing of individual cells poses a significant obstacle to long-term durability [127]. This issue is particularly critical as the overall stack performance is governed by its weakest

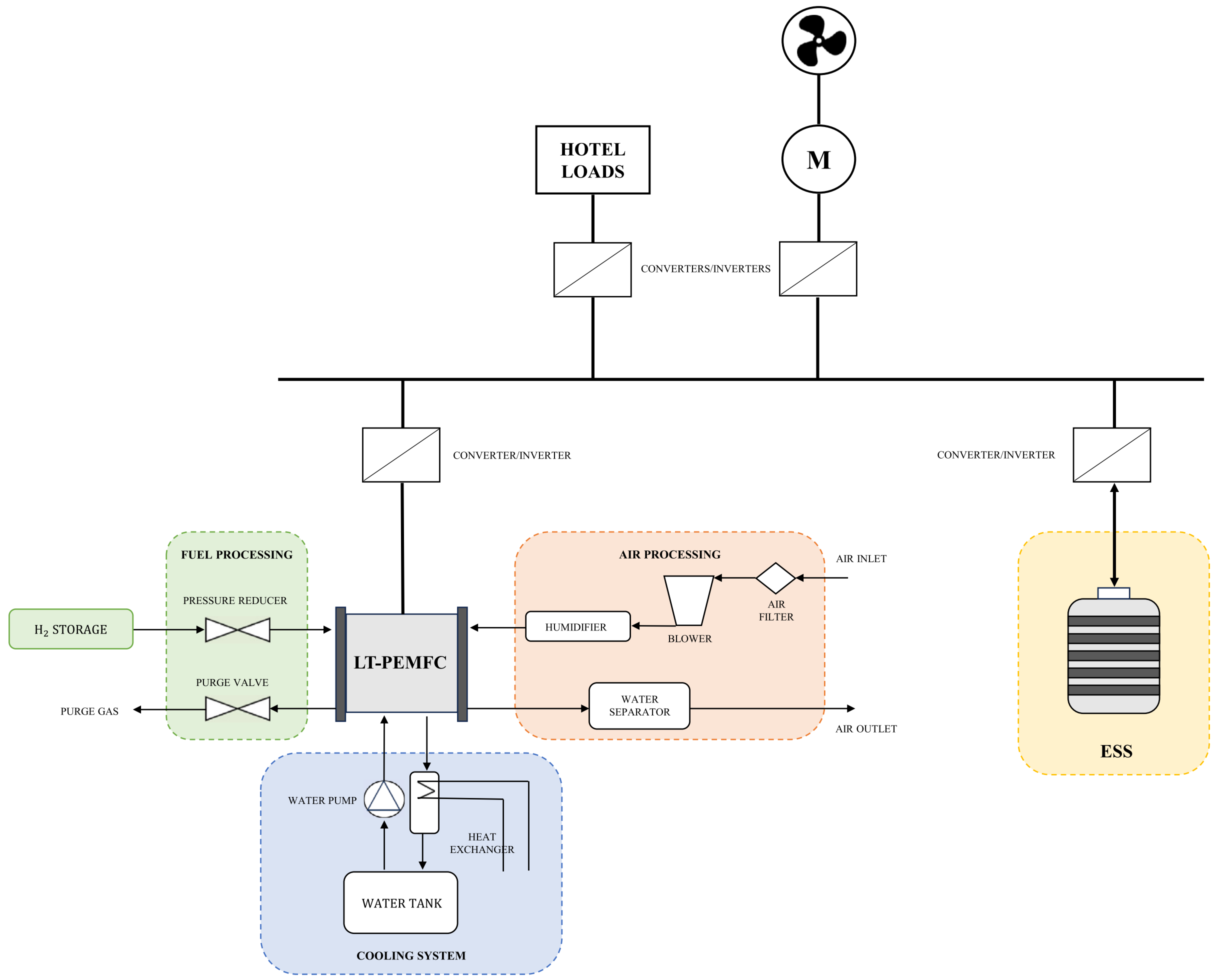

Fig. 4. Schematic of the topology of a typical maritime hybrid LT-PEMFC/ESS system, including BoP components for the fuel cell.

cells [128]. Previous research has highlighted several factors contributing to performance heterogeneity in stacks, including MEA degradation, structural stack design leading to uneven reactant distribution, and contamination effects that poison the catalyst [129]. Studies show that while single-cell analyses reveal fundamental degradation pathways, scaling to commercial-size stacks introduces more complex inhomogeneities within single cells [130,131]. In the maritime sector, where the power demand of vessels requires fuel cell systems in the hundreds of kilowatts, these effects become even more pronounced, making the control and prediction of performance heterogeneity a key issue for applications.

Beyond the stack, the durability of the overall power system is strongly influenced by the balance of plant (BoP) components. A typical BoP of a hybrid LT-PEMFC/ESS system is shown in Fig. 4, including the H_2 tank and processing system, air processing systems, cooling system, and power converters. BoP components affect the stack operation, and can also be affected by degradation. Saline air can cause material corrosion and salt crystal deposition in the air channels or blowers, causing obstruction. The combined effect of maritime degradation factors, such as inclinations and vibrations, will challenge BoP key functions such as water management and reactant distribution. Moreover, the continuous vibration environment experienced at sea can cause mechanical stress and sealing issues.

Considering the ESS, batteries, and in particular LIBs, are prone to performance degradation [126]. LIBs degrade both during cycling, when the battery is charged or discharged, and when in resting conditions (calendar ageing) [132]. LT-PEMFC stacks can also be coupled with supercapacitors, which, similarly to batteries, are subjected to both cycling and calendar ageing [133].

4.3. Material and design advancements

A possible route to improve LT-PEMFC durability is the optimisation of component design and materials [134]. As the application in the maritime sector is relatively recent, no dedicated research has yet focused on optimising components and stack design to withstand maritime-specific stressors more effectively. Nevertheless, insights can be drawn from automotive research, where the increasing demand for heavy-duty applications (also characterised by longer lifetime requirements and exacerbated degradation mechanisms) has driven research towards optimised materials and designs for durability enhancement [135,136].

Enhanced membrane durability is crucial considering the demanding load cycles of vessels that experience frequent load variations and extended operation times. Although Nafion-based membranes (PFSA) [137] remain the commercial standard for LT-PEMFCs, recent studies have shown that short-side-chain ionomers such as Aquivion are promising, exhibiting higher stability and improved degradation resistance under certain conditions [138,139]. Moreover, to balance the trade-off between thickness (lower thickness translates into higher proton conductivity) and mechanical stability, researchers have developed reinforcement strategies based on porous polymer layers, particularly expanded polytetrafluoroethylene (ePTFE), which has demonstrated promising results by enhancing mechanical and chemical stability while maintaining acceptable levels of proton conductivity [140,141].

Membrane optimisation research lines should be investigated under duty cycles representative of maritime applications and salt exposure. As highlighted in Section 3.2, NaCl contamination reduces membrane conductivity by occupying sulphonate sites with Na^+, and can intensify radical-driven polymer attack, thereby amplifying concerns about membrane durability. A promising investigated solution to counteract the chemical attack of radicals on the membrane polymer chain is the incorporation of radical scavengers that can effectively eliminate harmful radicals [142]. So far, Ce-based scavengers exhibit the highest radical scavenging capacity. However, they are susceptible to dissolution and may have poisoning effects on ionomers, thereby impacting proton conductivity and mass transfer [143]. Moreover, Ce-based additives are more prone to dissolution in the presence of chlorides, which increases the risk of migration into the catalyst layer in maritime applications, highlighting the need for further tailored research.

In parallel, optimisation of catalyst follows some key research lines: (1) alloying Pt with transition metals to adjust its selectronic structure and increase the number of active sites; (2) addition of thin carbon-shell coatings to contrast the dissolution and agglomeration of catalyst particles; (3) development of hybrid-structured catalysts that combine Pt nanoparticles with M-N-C (M = Fe, Co, etc.) to support the catalytic activity and stability of pristine Pt; and (4) exploring the use of corrosion-resistant supports alternative to carbon such as metal oxides and crystalline carbon [144]. These catalyst-optimisation lines are directly relevant for maritime LT-PEMFCs, especially considering that Cl^- ions could competitively adsorb on Pt, and accelerate Pt dissolution and redeposition.

Since the combined effect of vibration and wave-induced inclinations can intensify water-management issues, one effective strategy is to increase the hydrophobicity of the GDL and catalyst layer [145,146]. Treating these components with hydrophobic materials such as PTFE, which have both hydrophobic and hydrophilic pores, respectively enabling the passage of reactant gases and liquid water, improves water management capability. In addition, improved GDL roughness was also demonstrated to be effective in improving water management [46]. Another promising approach is to introduce a microporous layer modified with a hydrophobic material between the GDL and the catalyst layer, which reduces water flooding and stabilises transport pathways [147].

Beyond the GDL, optimisation of bipolar plate design plays a critical role in improving cell performance and reducing inhomogeneities within the stack [148,149]. Research in this area has focused on design and optimisation of flow channel configurations [150,151] and understanding the mechanisms of two-phase flow, particularly in the cathode side of the cell where water accumulation and oxygen starvation frequently occur under high current density operation [152,153]. Various flow field designs, including sinusoidal, conical, ramped fin, and serpentine geometries, have been explored to improve reactant transport, enhance drainage, and promote more uniform current density distribution across the active area [154–156]. Developing flow field geometries that promote stable two-phase transport across varying orientations is promising for maritime LT-PEMFCs, as ship motion can strongly affect reactant distribution and water management. In parallel, the higher corrosion risk associated with saline air should be addressed by selecting graphite-based plates or applying protective coatings to metallic plates to mitigate corrosion [157].

4.4. Mitigation and recovery strategies

The durability of LT-PEMFC/ESS systems depends on the applied energy management strategy that allocates the vessel power demand between the LT-PEMFC and the ESS [125]. Health-aware energy management strategies enable power sources to operate in the most efficient load ranges while minimising degrading operating conditions and limiting potentially stressful events [158,159]. Reducing and mitigating transient loads, as well as high load demands and idling, is beneficial for the durability of the LT-PEMFC [71]. Using the ESS to protect the stack from critical operating conditions can significantly minimise its degradation under demanding ship load cycles. For large maritime LT-PEMFC/ESS systems, the energy management strategies should also adopt measures to minimise uneven ageing of individual cells. Studies have proven that the optimal operating conditions for fuel cell stack output performance may differ from those for performance uniformity [128]. In this regard, maritime stacks would benefit from avoiding idling or sharp transients that create local fuel starvation and implementing current ramping strategies to distribute dynamic stresses more evenly across cells.

Durability also strongly depends on the quality of the reactant streams. In particular, air processing treatments hold significant importance to prevent LT-PEMFC chemical contamination at the cathode side [94]. For LT-PEMFC systems applied onboard ships in marine environments, particular attention should be given to NaCl contamination. Lamard et al. [101] analysed the impact of NaCl on an LT-PEMFC operating in a marine environment for 50 h, finding that the commonly used cabin air filter was not completely able to block NaCl particles. Given the highly impactful contamination effects, investing in effective filters to treat the oxidant flow is essential for LT-PEMFC operating in marine environments.

As filters might not be sufficient to prevent NaCl contamination completely, post-contamination recovery strategies may be required to increase durability [101]. Some studies have demonstrated the potential for performance recovery after NaCl contamination by cathode rinsing with N_2 and clean water. Lamard et al. [101] obtained an excellent regeneration for most of the short contamination tests, highlighting that, in the short term, contamination mechanisms might be mostly reversible. For longer contamination tests, partial performance recovery was not systematic, suggesting that an irreversible chemical degradation process might occur in the long run. Similarly, Park et al. [99] proved performance recovery was possible by applying a high potential to the cathode when contamination happened at lower voltages. This finding holds significant importance and suggests that further research in this area may yield tailored recovery strategies applicable during system operation onboard. In particular, distinguishing between reversible and irreversible degradation mechanisms depending on the contamination concentration, exposure time, and operating voltage is essential for the development of recovery strategies.

Based on current research evidence, scheduling periodic cathode rinsing with N_2 and clean water could partially recover the LT-PEMFC performance and mitigate long-term degradation effects. Another mitigation technique could involve minimising idling and high-voltage operation to prevent irreversible poisoning effects, while periodically applying high voltages to restore performance. However, most experimental studies used high NaCl concentrations over relatively short operational times. Briand et al. [102] suggested that at low NaCl concentrations and long exposure times, crystal deposition in the air channel and on the GDL surface is the most critical mechanism, indicating that higher flow-rate pressure or water rinsing of the channels may be necessary.

The current studies on the effects of vibrations and inclination caused by vessel motions pointed out cell operation in dehydrated and flooded conditions as the main effect, suggesting potential recovery strategies could be associated with the cell humidification and water management system [110,111]. For example, if the counter-flow mode is adopted, hydrogen gas at the anode inlet can be wetted by the water diffused from the cathode, which can not only prevent the anode from flooding, but also reduce the anode humidification requirement [46]. Meanwhile, flooding can also be mitigated by changing operating conditions, such as reducing pressure, increasing temperature, and sub-saturated gas streams [160].

A summary of possible durability enhancement strategies, considering both operational and design approaches, is provided in Fig. 5. A crucial enabler for both mitigation and recovery strategies is the integration of prognostics into the overall durability framework. Prognostics enable the prediction of performance losses before they become critical to the system, providing the necessary foresight to adapt system operation in real-time. Given its central role in durability enhancement, prognostic modelling for LT-PEMFCs is examined in the following section.

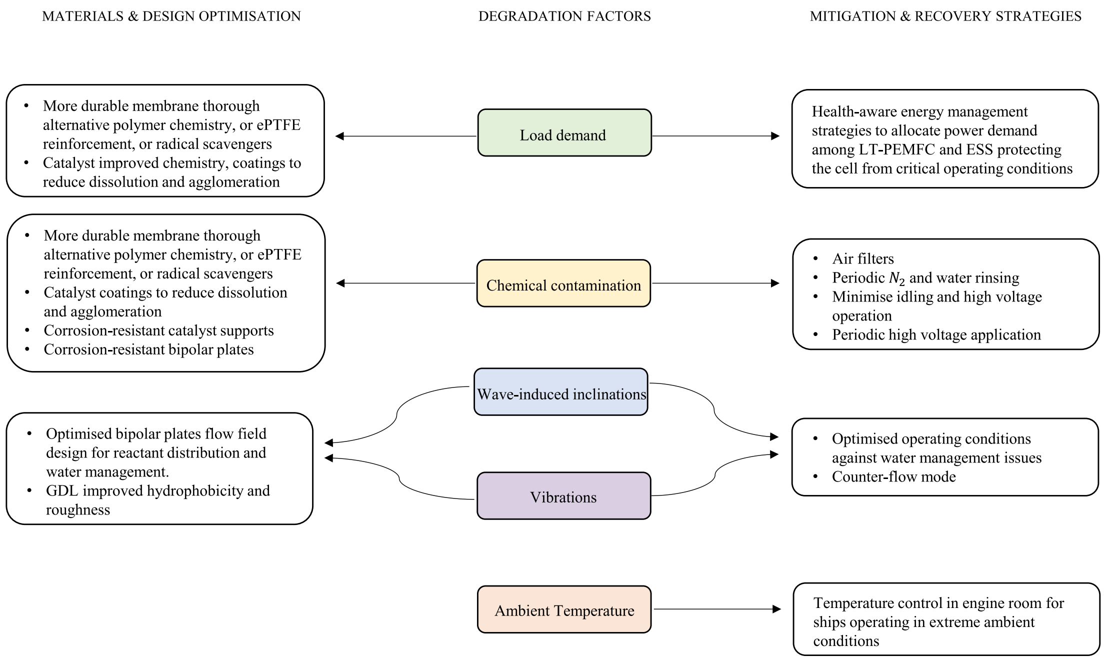

Fig. 5. Summary of mitigation and recovery strategies and of materials and design optimisations related to the analysed maritime degradation factors.

5. Prognostic modelling

In more mature sectors such as automotive, applying PHM strategies to LT-PEMFCs for lifetime prediction and durability enhancement has already gained high research relevance [14]. As shown in Fig. 6, a PHM framework begins with the data acquisition phase, which is typically conducted in a real operating system or during experimental testing, followed by data processing. Subsequently, health indicators are defined depending on the prognostic level (component, cell, stack). Voltage and power are the most common health indicators. Then, the end-of-life (EoL) criterion is defined, depending on the application requirements. In automotive, the United States Department of Energy defines EoL as equal to 10% power loss from the initial performance [161]. For maritime applications, there is no standard EoL indication so far. These preliminary phases are followed by the actual prognostic model development using the degradation dataset, according to the selected approach. Finally, based on the model estimation, durability enhancement strategies such as health-aware energy management or recovery strategies can be developed, and appropriate maintenance can be scheduled.

The key process in PHM is the development of the system performance model, which is used for performance degradation and RUL estimation [18]. Due to the limited experience in the sector, no prognostic model specific to shipping applications has been developed to date. Instead, the LT-PEMFC prognostic models available in the literature are primarily based on automotive applications. Here, three different approaches exist: model-based, data-driven, and hybrid. This section reviews the current state-of-the-art of existing LT-PEMFC models to explore their applicability in the maritime sector. Summarising tables of the analysed prognostic models can be found in Tables B.10, B.11, and B.12.

5.1. Model-based methods

A model-based approach for LT-PEMFC performance is based on the physics of the system and its degradation mechanisms [162]. Within model-based approaches, a distinction can be made between (i) physics-based models purely developed with mathematical equations describing the system's physics, and (ii) semi-empirical models developed by integrating empirical coefficients in physics-based equations.

Purely physics-based models are mainly applied at the component level, especially for the catalyst and membrane. Several models describing catalyst degradation have been developed building on the first approach proposed by Darling and Meyers [163], who formulated a kinetic framework for Pt dissolution that couples electrochemical oxidation, oxide formation, and chemical oxide dissolution through Butler–Volmer–type rate laws. Subsequent works extended this framework by incorporating particle growth via Ostwald ripening, the redeposition of dissolved Pt species, and carbon support corrosion, linking these processes to operating conditions [164]. Recently, some models have combined degradation mechanism models to predict Pt particle size distribution, which is used to estimate ECSA reduction [165,166].

One way of modelling electrolyte membrane degradation is based on its thickness reduction [167]. Other physics-based approaches model chemical degradation by radicals attack, which leads to fluoride emission and loss of proton conductivity [168]. In addition to radical-driven pathways, mechanical stress models account for cyclic hydration and dehydration that cause swelling–shrinking stresses and crack propagation [169].

At the cell and stack level, semi-empirical models are widely used. These typically build on the polarisation curve model, expressed as:

$$V_{cell} = E_{rev} - V_{act} - V_{ohm} - V_{conc}, \tag{1}$$

Where:

- E_{rev} is the cell maximum attainable voltage, also known as Nernst voltage or reversible voltage [], given by:

$$E_{rev} = -\frac{\Delta G^0}{nF} + \frac{RT}{nF}\ln\left(\frac{P_{H_2}\sqrt{P_{O_2}}}{P_{H_2O}}\right) \tag{2}$$

  ΔG^0 is the Gibbs free energy of the reaction at operating temperature (T) and reference pressure, R is the ideal gas constant, n is the number of electrons transferred in the electrochemical reaction, F is the Faraday constant, and P_x is the partial pressure of the reactant.
- V_{act} are the activation losses originating from the polarisation potential needed to drive the electrochemical reaction and dominate the cell performance at low current densities.

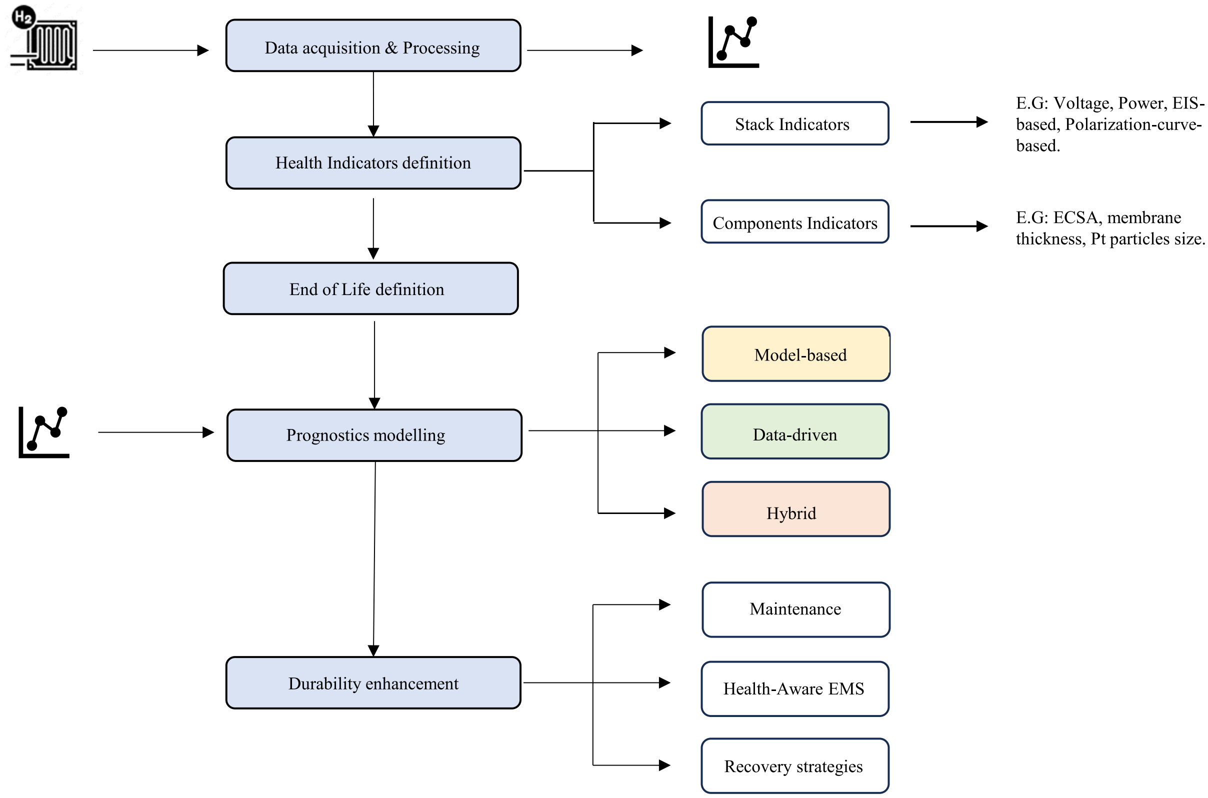

Fig. 6. Schematic of Prognostics and Health Management (PHM) framework integration for LT-PEMFCs.

- V_{ohm} are the ohmic losses due to the ionic resistance of the electrolyte and electronic resistance of the electrodes, dominating the cell performance at intermediate current densities.
- V_{conc} are the concentration losses caused by mass transport limitation and characteristic of high current densities.

Different semi-empirical equations have been proposed to model activation, ohmic, and concentration losses as functions of current density and several other parameters. Including the ageing effects in such models requires identifying the parameters that degrade over time and incorporating their time-dependent degradation trends into the modelling equations. An example of a semi-empirical model based on this approach was developed by Jouin et al. [23]. In their work, the identified degrading parameters are modelled using semi-empirical time-dependent equations, allowing the voltage model to become a function of time and enabling the prediction of its degradation evolution. Other scholars developed semi-empirical models by integrating voltage degradation models with Particle Filtering [170–172], Unscented Kalman Filter [172,173], and Extended Kalman Filter [174] to capture the evolution of the degradation parameters from empirical data.

As explained in Section 4.2, inhomogeneities resulting from uneven ageing of individual cells pose durability challenges and directly influence stack prognostics. Integrating such effects requires more complex models that consider multi-physics coupling factors. Tang et al. [128] proposed a semi-empirical modelling strategy that accounts for inhomogeneities by coupling multi-point impedance and voltage measurements with a current–voltage redistribution model. Instead of treating the stack as an equipotential unit, their framework quantifies cell-to-cell voltage divergence, linking it to single-cell inhomogeneities in species transport and water management. This enables the identification of cells or regions most susceptible to accelerated degradation and provides heterogeneity metrics that can serve as prognostic indicators. Zhao et al. [175] proposed a 2D multi-physics stack model combined with an empirical degradation framework that tracks hydrogen crossover, membrane conductivity loss, and ECSA reduction. By monitoring single-cell voltage and degradation rates, their model shows that some cells degrade more rapidly under local stresses. In maritime applications, where stacks reach hundreds of kilowatts, such methods are critical for accurate RUL prediction and reliable estimation.

5.1.1. Advantages and limitations of model-based methods

The main advantages of model-based methods are their strong generality and limited training data requirement [19]. However, LT-PEMFCs are dynamic, non-linear, multi-physics electrochemical systems whose performance degradation and failure modes vary under different operating conditions [176]. The development of such models presents challenges, as the physics underlying many degradation mechanisms remains unclear or complicated to translate into generic analytic forms that relate to the operating conditions [20].

Physics-based modelling is well-suited for predicting specific degradation mechanisms and is particularly effective for prognostics at the component level. Once a physics-based model of a component has been developed, it can be transferred to any application, given that the degradation is linked with generalised operating conditions. Since electrodes and electrolyte membranes are recognised as the most critical components for cell degradation, their modelling is sometimes used to approximate the RUL of the entire cell or stack [23]. For example, the overall voltage decay can be estimated from the ECSA reduction for RUL estimation [177]. However, prognostics at the component level mainly consider components separately, and coupled phenomena are not taken into account, resulting in a higher risk of inaccurate degradation prediction for cells and stacks [178]. The lack of complete physical knowledge and the system's intrinsic complexity make a purely physics-based approach unfeasible at the stack level.

In contrast, semi-empirical models are more suitable for prognostics at the stack level. These models can also be extended to include single-cell inhomogeneities, improving prognostic accuracy by identifying the weakest cells and capturing how uneven ageing drives stack failure.

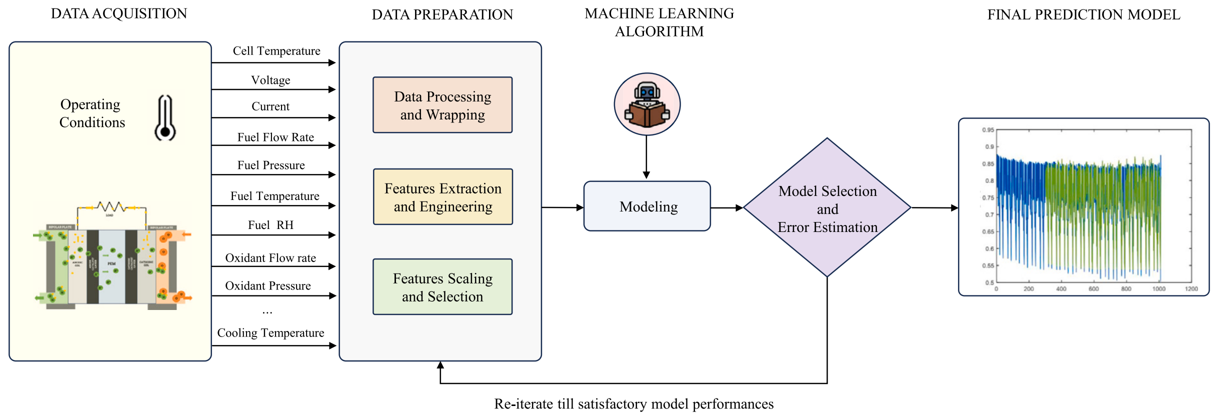

Fig. 7. Schematic of the procedure to develop a data-driven prognostic model for LT-PEMFCs.

In this case, the complexity of the multi-physics model presents an additional challenge to be considered. Moreover, the definition of empirical degradation parameters relies on experimental degradation studies and on the availability of degradation datasets. Single-cell data measurements increase the testing complexity and require the definition of additional degradation parameters in the model. Defining empirical degradation parameters and coupling multi-physics effects remains difficult to generalise across stacks, especially for dynamic operation.

5.2. Data-driven methods

A data-driven model applies machine learning algorithms to predict the system's behaviour using historical and real-time data [179,180]. Since it lacks an intrinsic physics-based link between its inputs and outputs, this approach is also referred to as the black-box model [22]. Traditional Neural Networks, Echo-Sate Networks [181–183], Long Short Term Memory Networks [64,184,185], Adaptive Neuro-Fuzzy Inference Systems [186], Convolutional Networks [187,188] are the most commonly applied algorithms for LT-PEMFC performance prediction and RUL estimation.

Fig. 7 illustrates the data-driven modelling approach for LT-PEMFCs. The process begins with collecting and cleaning operational data, forming a comprehensive dataset that captures the system's dynamics and performance degradation [189,190]. Key features are extracted and scaled to reduce the dataset size and optimise machine learning models [191]. The models are then trained to predict cell performance based on these inputs, following the model selection and error estimation procedure explained in [192]. The selected model is then applied to make performance predictions over time. To improve generalisation and avoid overfitting, several strategies can be employed, including cross-validation, dropout, and regularisation techniques, as well as early stopping during training [193]. In addition, careful selection of input features and data augmentation can further mitigate the risk of models adapting too closely to noise rather than underlying degradation patterns. Finally, model validation is done by comparing predicted and actual performance metrics, ensuring accuracy and robustness for reliable long-term predictions.

Researchers are actively making improvements in terms of accuracy and model adaptability with data-driven prognostic methods, such as using self-selection of key parameters in neural networks [185] or combining neural networks with traditional time series forecasting models [194]. Chen et al. [195] adopted the Wavelet neural network to analyse the global LT-PEMFC degradation trend and reversible phenomena. The parameters and the number of neurons in the hidden layer of the neural network are optimised by the Cuckoo search algorithm to enhance the prediction performance. Wang et al. [194] coupled the long short-term memory network with the differential evolution optimisation algorithm. In contrast, Chen et al. [196] optimised the same machine learning algorithm with the Bayesian method. Recently, convolutional neural networks proved to be more efficient than recursive strategies in understanding temporal dependencies and have been proposed as a further improvement for LT-PEMFC prognostics. Wilberforce et al. [187] demonstrated the increased prediction accuracy of a recurrent neural network combined with a convolutional neural network. Sun et al. [188] applied a convolutional neural network combined with a long short-term memory network, developing a prediction algorithm to predict the degradation of each component.

Recently, the gate recurrent unit (GRU) algorithm has been applied for LT-PEMFC prognostics and optimised with different techniques such as particle swarm optimisations [197] and WaveNet generative model [198]. Many of the applied optimisation strategies also act as safeguards against overfitting, either by constraining model complexity (e.g., hyperparameter tuning with Cuckoo search [195], Bayesian optimisation [196], or particle swarm optimisation [197]), or by improving generalisation through hybrid architectures [187,188].

Most of the analysed data-driven methods predict stack performance as a whole, overlooking the contributions of individual cells. However, if single-cell data are available, heterogeneity can be captured using statistical methods. Ma et al. [199] utilised transfer learning and similarity-based sample selection to capture single-cell differences, enabling the model to adapt to uneven ageing across cells.

5.2.1. Advantages and limitations of data-driven methods

Data-driven techniques offer a powerful tool for predicting degradation, considering the effects of physics that are yet unknown through data. For complex systems such as LT-PEMFCs, this approach seems particularly appealing. Prediction algorithms can achieve good accuracy and high computational efficiency in the implementation process when proper training is ensured [22]. Nevertheless, the absence of explicit physical links between inputs and outputs limits their interpretability. Degradation is treated as a whole-system phenomenon, hindering the identification of degradation causes and mechanisms. In LT-PEMFC, where degradation is a complex combination of various phenomena, this lack of mechanistic insight limits the trust and interpretability of the models, posing limitations for durability enhancement.

Data-driven algorithms highly rely on the availability and quality of extensive datasets, which limits the model's ability to generalise to new scenarios, increases the risk of overfitting, and makes it sensitive to noise and outliers in data [14]. Furthermore, computational challenges related to the model's complexity need to be considered. While neural networks, especially advanced architectures like Convolutional Neural Networks or Long Short-Term Memory Networks, can model complex temporal dependencies, they also require significant computational power, particularly during the training phase. The tuning of hyperparameters, or optimisation techniques (e.g., Cuckoo search algorithms,

Table 7
Comparison of advantages and disadvantages of prognostic modelling approaches for LT-PEMFCs.

Method		Advantages	Disadvantages
Model-based	Physics-based	High physical interpretability Captures specific mechanisms Transferable across applications Limited data need	Applied only for components Requires complex physics knowledge
	Semi-empirical	Balance between physics and data Low computational cost	Relies on empirical rates Limited generalisation
Data-driven		High prediction accuracy No physics knowledge required	No physical interpretability Requires extensive data Sensitive to noise/overfitting High computational cost
Hybrid		Combines physical interpretability and accuracy Reduced data needs Robust to variability Transferable across applications	Requires quality data Requires physics knowledge High computational cost

differential evolution), can drastically affect performance and computational cost. Achieving the right balance between computational efficiency and prediction accuracy is challenging.

5.3. Hybrid methods

Hybrid models combine physics-based and data-driven methods [20]. The physical laws governing the systems are incorporated through physics-based modelling equations, while machine learning algorithms are used to handle complex degradation trends and uncertainties, not easily captured by traditional physics-based models. Most of the analysed hybrid methods include a general physics-based voltage model, where neural networks or regression-based algorithms predict degradation.

Zhou et al. [200] proposed a stack voltage physical ageing model trained on a degradation dataset by a particle filter and integrated with an autoregressive moving average and a time delay neural network. The method was compared with linear, logarithmic, and exponential-based hybrid prognostics, demonstrating high forecasting accuracy and robustness, which led to reliable RUL estimates for online prognostics. Liu et al. [201] proposed a hybrid prognostic framework composed of two phases. The first phase involves predicting the long-term degradation trend using an autoregressive machine learning algorithm. In the second phase, the semi-empirical degradation model of LT-PEMFCs is developed, and the Unscented Kalman Filter is used to estimate the RUL. Results showed that the proposed hybrid framework is more accurate than other purely data-driven techniques, such as the adaptive neuro-fuzzy interference system method.

Xie et al. [202] combined the particle filter and the long-short term memory recurrent neural network, obtaining a percentage error lower than 10% under different training phases. In contrast, it can be larger than 20% for the model-based method. Moreover, they demonstrated that the hybrid method is more robust to external disturbances compared to the single model-based method or data-driven methods. Similarly, Pan et al. [203] proposed a combined model-based adaptive Kalman filter and data-driven NARX neural network method, which demonstrated better performance compared to the single NARX method.

Ma et al. [204] combined a voltage model with a Kalman filter and the long short-term memory recurrent neural network. In [205], an electrochemical impedance spectroscopy model-based method is developed with particle filter and random forest regression. The obtained performance was higher compared to the long short-term memory method. Recently, Hu et al. [206] combined a Wiener process with the Kalman filter model-based method, a transformer structure, and a Monte Carlo dropout method, which resulted in less effectiveness than the long short-term memory method. Similarly, Ko et al. [207] proposed a physics-informed neural network including governing equations elucidating membrane and catalyst degradation mechanisms, which demonstrated proficient RUL prediction while mitigating reliance on ageing test data.

5.3.1. Advantages and limitations of hybrid methods

Combining the strengths of both data-driven algorithms and physics-based approaches, hybrid methods are generally effective for LT-PEMFC prognostics. Since they need fewer parameters than single data-driven models, the modelling process is simplified. Moreover, they can achieve high prediction accuracy while maintaining the physical interpretability of degradation, capturing cell-level variability when sufficient measurement resolution is available [15]. Because hybrid models are grounded in both physical laws and learned behaviours from data, they tend to generalise better across different operating conditions. This means they are more resilient to changes in system behaviour and external factors that might be absent in the training data.

Although hybrid models reduce the dependency on large datasets, they still require high-quality degradation data for accurate predictions. Moreover, as they combine multiple modelling techniques, they can become computationally expensive, especially when the degradation complexity is high. Techniques like particle filters, neural networks, and Kalman filters all require significant computational resources, especially when used in real-time online prognostics. While the integration of physics and data brings several advantages, finding the right balance between the two modelling approaches proves challenging. Over-reliance on the physics-based part of the model may limit the system's ability to adapt to unforeseen behaviours. In contrast, over-reliance on the data-driven part may lead to the same pitfalls as pure machine learning models.

5.4. Degradation datasets for model development

Model development relies on operational datasets containing information on degradation trends. The employed dataset significantly impacts the reliability and accuracy of the model [178]. An overview of employed datasets for prognostics is shown in Table 8. The open-source IEEE PHM 2014 challenge dataset is currently the most applied one [208]. It was obtained through long-term experiments conducted on two LT-PEMFC stacks, each composed of five single cells with an active area of 100 cm^2. The first stack was operated under a constant load current of 70 A, while the second was operated under a semi-dynamic load with a nominal current of 70 A and 10% triangular current ripples at 5 kHz frequency (defined as semi-dynamic load profile). An overview of voltage and current over the overall testing time for both stacks is shown in Fig. 8. Although this specific dataset has been widely applied for developing prognostic models, it is not fully representative of the ageing process that the LT-PEMFC stacks experience in real applications. While constant-load operation induces an almost linear degradation trend, dynamic vehicle or ship load demands are more likely to cause non-linear voltage degradation, influenced by both operating and environmental conditions.

More representative datasets are generated with long-term durability tests based on drive-cycle-based testing protocols. Drive-cycle-based protocols are based on a set of assumptions regarding the operation

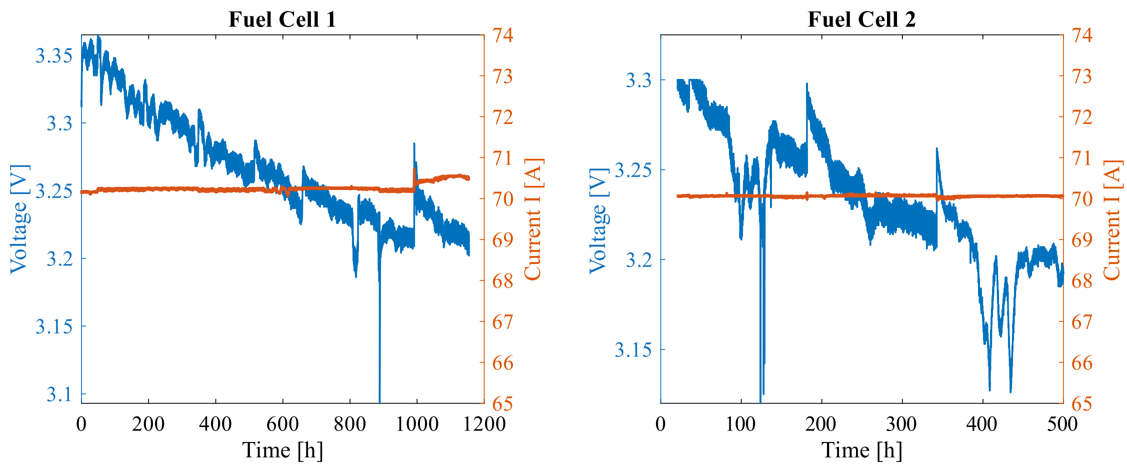

Fig. 8. Current and voltage evolution of the LT-PEMFC stack tested at constant current (Fuel cell 1) and the LT-PEMFC stack tested with current ripples (Fuel cell 2), from the PHM 2014 challenge dataset widely used for prognostics [208].

of fuel-cell-powered vehicles. For example, the European harmonised test protocols for PEMFC testing in single-cell configuration for automotive applications are based on the NEDC, which represents typical vehicle operating conditions in busy European cities, characterised by low engine loads and a maximum speed of 50 km/h [209]. Robin et al. [210] aged a 30-cell stack with a current profile adapted from the NEDC. Another dataset was developed by Zuo et al. [211], where a single LT-PEMFC was tested with the NEDC repeated for 1000 h. Ou et al. [212] conducted a durability experiment on a 15-cell stack, under the NEDC load profile, for 425 h, and on a second stack using a specific locomotive mission profile for 505 h.

Some prognostic models are based on on-road automotive LT-PEMFC degradation datasets. Hu et al. [213] developed a lifetime prediction model analysing an LT-PEMFC city bus running in Beijing. The bus had a typical hybrid powertrain system where the stack is coupled with a battery pack, and operated a daily operational cycle for five months. The same dataset was used by Pei et al. [214] to develop a prognostic method based on the four typical operating conditions, and the related voltage degradation coefficients reported in Table 2. Chen et al. [215] developed a model-based prognostic method using an on-road degradation dataset from the MobyPost project, where the LT-PEMFC system is integrated with LIBs in a hybrid vehicle to minimise the transients experienced by the stack. Juin et al. [23] tested their prognostic model on a dynamic dataset where the LT-PEMFC stack was aged with a specific automotive mission profile for 1200 h. Yue et al. [216] used a long-term degradation dataset from an experiment carried out in FCLAB Research Federation. The stack modules were tested with a dynamic load profile acquired in real operating conditions for hydrogen bikes.

To date, only Choi et al. [88] have developed an experimental test based on a specific ship load profile, but the resulting dataset is not publicly available and has not been utilised in prognostic modelling. All long-term datasets currently used for prognostic modelling are based on experimental simulations of automotive load cycles. These datasets are not representative of maritime applications, as ship operations vary by vessel type and differ significantly from automotive operations. The availability of new datasets representative of maritime operations is essential for developing tailored prognostic models. In this regard, defining standardised maritime load cycles that reflect realistic load profiles of various ship applications is necessary for designing representative durability tests.

5.5. Model applicability for maritime LT-PEMFCs

Since the limited experience hindered the development of LT-PEMFC prognostic models for shipping applications, automotive-based models were reviewed to analyse their applicability in the maritime sector. An overview of general advantages and disadvantages of the analysed modelling strategies is provided in Table 7.

The physics-based models at the component level have high generality and can potentially be implemented for degradation prediction in maritime applications. In particular, catalyst and electrolyte membrane degradation models provide a baseline for integrating maritime-specific effects, such as NaCl-related degradation mechanisms.

Semi-empirical models used in automotive could be adapted to a maritime context. Currently, most models focus on load-induced degradation. Although the empirical automotive degradation rates reported in Tables 2 and 3 have been applied in the modelling of maritime systems, the different nature of the application could lead to inaccurate predictions. The effective development of similar strategies for maritime applications requires conducting tailored durability tests and measuring new degradation rates. Moreover, this modelling approach simplifies real operating profiles as a combination of generalised operating phases, such as high load, low load, transients, etc. The accuracy of the prediction depends on how these operating conditions are defined and on the consequent definition of the related empirical degradation rates. This approach oversimplifies degradation by neglecting the superposition of effects into different operating phases and by assuming linear degradation trends. Therefore, research should focus on simplifying ship characteristic operating profiles with more realistic methodologies and on defining new empirical degradation rates with experimental testing.

Data-driven models, particularly deep learning architectures such as neural networks, represent a powerful tool for predicting the behaviour of complex systems, like LT-PEMFCs. However, they require extensive, high-quality datasets that represent degradation over time under different operating conditions. Such datasets are often scarce for LT-PEMFC applications, and currently non-existent in maritime contexts. Since developed algorithms were primarily trained on datasets with constant loads or automotive driving cycles, they may lose accuracy when transferred to maritime applications with different operating scenarios. Moreover, the lack of a link between degradation and its physical causes limits the application of machine-learning algorithms for durability enhancement.

Hybrid models could both (i) provide insights into the physical processes of degradation, and (ii) optimise the prediction with data-driven algorithms. Therefore, they represent a promising direction for enhancing the reliability, accuracy, and explainability of LT-PEMFC prognostic models across various applications. In the future, this could help to bridge the gap between the power of data-driven prediction methods and the need to understand complex degradation scenarios in maritime applications.

Table 8
Overview of long-term LT-PEMFC degradation datasets used in prognostic models.

Reference	System	Test duration	Operating conditions	Public availability
IEEE PHM 2014 [208]	5-cell stack	1000 h/500 h	Constant load, semi-dynamic load	✓
Robin et al. [210]	30-cell stack	2000	Constant load/NEDC	✗
Zuo et al. [211]	Single cell	1000 h	NEDC	✓
Ou et al. [212]	15-cell stack	425 h/505 h	NEDC/Locomotive profile	✗
Hu et al. [213]	Hybrid bus	5 months	Real bus operation	✗
Chen et al. [215]	Hybrid vehicle	Not specified	Real vehicle operation	✗
Juin et al. [23]	Stack	1200 h	Automotive mission profile	✗
Yue et al. [216]	Stack module	1500 h	Real bike operation	✗
Choi et al. [88]	Stack	300 h	Ship load profile	✗

Regardless of the adopted strategy, large maritime stacks will require the incorporation of methodologies that account for single-cell inhomogeneities to achieve accurate prediction. Moreover, the development of prognostic models will strictly depend on the availability of long-term degradation datasets. Considering the variety of maritime applications, the durability tests should be based on reference operating scenarios of different ship types. In this regard, the definition of standardised ship load profiles would be highly beneficial.

Ultimately, since maritime applications exacerbate many degradation factors, load-profile-based prognostic approaches typical of automotive applications might not be sufficiently accurate for maritime LT-PEMFCs. Therefore, the superimposed effect of other major degradation factors, such as NaCl contamination, vibrations, and wave inclinations, could be included in future maritime prognostic models.

6. Conclusions

Enhancing the durability of LT-PEMFCs in maritime applications requires a deep understanding of degradation mechanisms and the development of accurate, application-specific prognostic models. This review comprehensively discussed the durability and applicability of prognostic modelling for maritime LT-PEMFCs. Load cycling emerged as the most influential factor due to the highly variable and continuous operating conditions typical of ships. NaCl contamination affects core components of the cell, and although partial recovery has been proven possible, the long-term degradation effects require further investigation under realistic maritime conditions. Static and dynamic inclinations influence water management and reactant distribution, potentially accelerating membrane and catalyst degradation, yet dynamic effects remain largely unexplored. Similarly, while low-level vibrations may enhance performance, high-amplitude vibrations in maritime applications could contribute to long-term degradation of components such as GDL, bipolar plates, and BoP components. The superimposed effect of these degradation drivers will create a particularly challenging environment for the durability of LT-PEMFC systems that requires tailored research.

Accurate prognostic models are a crucial step for the development of durability enhancement strategies. Considering the importance of physical interpretability for durability enhancement, semi-empirical model-based and hybrid approaches are promising for future developments. However, prognostics for maritime applications are hindered by the limited understanding of complex degradation scenarios and by the absence of representative datasets. To address the gaps identified in this work, the following research directions are suggested:

- Investigating the effect of maritime load cycles on LT-PEMFC degradation, considering the variety of ship applications, and the ESS contribution in minimising degradation. This is essential for the development of prognostic models and to inform health-aware energy management strategies.
- Investigating the impact of NaCl degradation mechanisms considering realistic concentrations. Distinguish between reversible contamination effects and irreversible degradation mechanisms, assessing the impact of operating conditions and exposure time.
- Testing combined dynamic wave-induced inclinations and vibrations with amplitude and frequency characteristic of ships, to investigate the degradation effect of repeated flooding/dehydration cycles, and uneven fuel and oxidant distribution.
- Developing experimental durability protocols considering various operational profiles reflecting the diversity of ship types to collect long-term datasets for model development. In this regard, the definition of standardised load cycles for different ship applications is needed.
- Integrating physical understanding of degradation into prognostic models, considering the combined effect of degradation factors (instead of solely load demand) and single-cell uneven ageing.

The outcome of these research lines will provide further insights for the understanding of degradation and development of lifetime prediction models, which represent fundamental steps for durability enhancement. This will enable more cost-effective, safe, and efficient application of LT-PEMFC systems on board of ships, facilitating the decarbonisation of the maritime sector.

CRediT authorship contribution statement

Sara Tamburello: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Lindert van Biert:** Writing – review & editing, Supervision, Methodology. **Andrea Coraddu:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Table of LT-PEMFC commercial systems

See Table A.9.

Appendix B. Summarising tables of the analysed prognostic models

See Tables B.10–B.12.

Table A.9
Characteristics of commercial LT-PEMFC systems designed for maritime applications.

Supplier	Model	Nom. Power (kW)	Nom. Efficiency (%)	Nom. Specific Power (W/kg)
Ballard	FCwave	200	53.5	200
Nedstack	PemGen 3	700	52	163
Nedstack	PemGen Mobile	100	50	154
Genevos	HPM-40 Gen II	40	54	160
Genevos	HPM-250 Gen II	250	50	300
PowerCell group	Marine System 225	225	–	225
PowerCell group	Marine System 250	250	45	42
Toyota EODev	REXH2	70	30	130
Convus Energy	Pelican	340	–	90
INOCEL	Z300 - M	200	50	500

Table B.10
Summary of model-based prognostic models.

Study	Physical model	Load	Prognostic level	Accuracy
Kosoglu et al. [217]	Physics-based catalyst degradation	Constant with RH cycle	Component	Not assessed
Zhang et al. [218]	Semi-empirical catalyst degradation	Cycling square profile	Component	95% confidence interval
Lechartier et al. [179]	Physics-based voltage degradation	Constant, semi-dynamic	Stack	RMSE=0.5103
Juin et al. [170]	Semi-Empirical voltage degradation	Constant	Stack	MAPE=0.574%
Bressel et al. [174]	Semi-empirical voltage degradation	Constant	Stack	6% confidence interval
Kim et al. [219]	Semi-empirical voltage degradation	Constant, semi-dynamic	Stack	Average weighted-sum error=5.32e−6
Juin et al. [23]	Semi-empirical voltage degradation	Automotive driving cycle	Stack	Not assessed
Robin et al. [210]	Semi-empirical voltage degradation	NEDC	Stack	Not assessed
Zhang et al. [67]	Semi-empirical voltage degradation	Constant	Stack	Not assessed
Koltsiva et al. [220]	Physics-based catalyst degradation	Not applicable	Component	Not assessed
Hu et al. [213]	Semi-empirical ECSA model	Automotive driving cycle	Stack	1% deviation
Zhang et al. [171]	Semi-empirical voltage degradation	Simulated dynamic load	Stack	Not assessed
Chen et al. [173]	Semi-empirical voltage degradation	Automotive driving cycle	Stack	RE=2.03%
Pei et al. [214]	Semi-empirical voltage degradation	Automotive driving cycle	Stack	Not assessed
Chang et al. [221]	Physics-based catalyst degradation	Automotive driving cycle	Component	Not assessed
Ao et al. [222]	Semi-empirical catalyst degradation	Automotive driving cycle	Stack	RE=8.18%
Ou et al. [212]	Semi-empirical voltage model	NEDC	Stack	RMSE=0.018
Wang et al. [223]	Semi-empirical polarisation curve model	Constant	Stack	RMSE=0.00127
Zhang et al. [172]	Semi-empirical voltage model with Multi-point Square-root enteral difference Kalman filter	Constant, semi-dynamic	Stack	RMSE=0.00270 and 0.00135

Table B.11
Summary of data-driven prognostic models.

Study	Data-driven Technique	Load	Prognostic level	Accuracy
Vianna et al. [224]	Linear + High order polynomial regression	Constant	Stack	MSE=7.89e−6
Silva et al. [186]	Adaptive Neuro-Fuzzy Inference system	Constant	Stack	$R^2 > 0.95$
Javed et al. [225]	Ensemble of constraint based Summation Wavelet — Extreme Learning Machine models	Constant, semi-dynamic	Stack	$R^2 > 0.91$
Morando et al. [181]	Echo State network	Constant	Stack	MAPE=0.97%
Liu et al. [226]	Group method of handling data + Wavelet analysis	Constant, semi-dynamic	Stack	Stack1 RMSE=0.09, Stack2 RMSE=0.06
Zhu et al. [227]	Gaussian process	Constant	Stack	10% interval accuracy
Ma et al. [184]	Grid Long Short-Term Memory recurrent neural network	Constant	Stack	RMSE=0.004
Li et al. [182]	Echo State network	Dynamic	Stack	Not assessed
Chen et al. [215]	Grey neural network + particle swarm optimisation + moving window method	Constant, dynamic	Stack	MAPE < 1.04%
Hua et al. [228]	Multiple inputs and outputs Echo State Network	Constant, semi-dynamic	Stack	RMSE=0.011
Vichard et al. [183]	Echo State network	Automotive driving cycle	Stack	NRSME=0.098
Chen et al. [195]	Walvet Neural Network + Cuckoo Search Algorithm	Dynamic	Stack	MAPE=5.19%
Zhang et al. [185]	MIMO long short-term memory + evolutionary algorithm hyperparameters selection	Constant, semi-dynamic	Stack	RMSE=0.00532 and 0.00538
Zuo et al. [211]	Attention based Recurrent neural network	Automotive driving cycle	Stack	RMSE < 0.004
Yue et al. [216]	Multi step echo state network optimised with genetic algorithm	Automotive driving cycle	Stack	RMSE=0.051
Wang et al. [194]	Long-short term memory + differential evolution optimisation algorithm	Constant, dynamic	Stack	RE=13.73%
Legala et al. [229]	Artificial Neural Network and Support Vector Machine Regressor	Constant, semi-dynamic	Stack	$R^2 > 0.99$
Wilberforce et al. [187]	Convolutional neural network and the recurrent neural network	Constant, semi-dynamic	Stack	RMSE=0.2581254
Sun et al. [188]	Convolutional neural network + long short-term memory with multi-head self-attention layers	Constant, semi-dynamic	Stack	RMSE=0.01785
Chen et al. [196]	Bidirectional long short-term memory neural network + Bayesian optimisation	Constant, semi-dynamic	Stack	MAPE=0.1245%
Kebede et al. [230]	Variational autoencoder and bi-directional long short-term memory with an attention mechanism	Constant, semi-dynamic	Stack	RMSE=0.00303, RMSE=0.00568
Izadi et al. [198]	WaveNet-GRU model	Constant, automotive driving cycle	Stack	RMSE=0.0031
Zhao et al. [197]	GRU optimised with particle swarm	Constant	Stack	RMSE=0.00472

Table B.12
Summary of hybrid prognostic models.

Study	Physical model	Data-driven Technique	Load	Prognostic scale	Accuracy
Zhou et al. [200]	Voltage degr. model + Particle Filter	Auto-regressive moving average model + time delay neural network	Constant	Stack	error on estimated RUL < 30%
Liu et al. [201]	Semi-empirical voltage degradation model + adaptive unscented	Adaptive neuro-fuzzy inference system	Constant, semi-dynamic	Stack	Confidence interval 94.5%
Xie et al. [202]	Voltage degradation model + Kalman Filter	Long-short term memory recurrent neural network	Constant	Stack	RMSE=0.0048
Pan et al. [203]	Voltage degradation model + Kalman Filter	NAXR neural network	Constant, semi-dynamic	Stack	0.0065 with 80% dataset
Ma et al. [204]	Voltage degradation model + Kalman Filterextended Kalman filter	Long-short term memory recurrent neural network	Constant, semi-dynamic, dynamic	Stack	RMSE=0.0110, 0.0262, and 0.0317
Peng et al. [205]	Equivalent circuit model based on EIS + Kalman Filter	Random-Forest Regression	Static, semi-dynamic	Stack	RMSE=0.0090
Hu et al. [206]	Voltage degradation model + Kalman Filter	Transformer network + Monte Carlo dropout	Static, semi-dynamic	Stack	RMSE=0.3845
Ko et al. [207]	Voltage degradation model	Neural network	Static, semi-dynamic	Stack	RUL accuracy 95.21%, 99.53%

Data availability

No data was used for the research described in the article.

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