WAVES OF CHANGE

MONACO HYDROGEN ALLIANCE

The Future of Hydrogen Mobility in Coastal Areas

JUNE 2025

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Foreword

Today's small vessel sector—yachts, ferries and workboats—faces a choice: continue with rising emissions and tighter rules, or turn to cleaner solutions that meet both performance and environmental goals. Hydrogen propulsion and fuel cells offer a clear way forward—delivering zero-emission power, solid range, and fast refueling, all while easing pressure on sensitive coastal areas. Making this shift work means more than new engines; it calls for shared refueling hubs, aligned regulations, and close collaboration between public bodies and industry players.

While battery systems often fall short on longer routes or heavier loads, hydrogen's higher energy density and the possibility of floating refueling stations powered by offshore renewables open up new opportunities for owners and operators. At the same time, costs, varied national rules and safety concerns must be addressed. Success will depend on shipbuilders, regulators, financiers and local communities working together to set clear standards, learn from early demonstrations and support each other through the transition.

This white paper draws on technical findings, economic analysis and practical policy suggestions from the Monaco Hydrogen Alliance, ENOWA-NEOM, and the International Taskforce on Hydrogen Mobility in Coastal Areas, which counts among its members several leading startups and established companies working on cutting-edge hydrogen technologies. Our aim is to help decision-makers move from ideas to action, so hydrogen can help meet net-zero ambitions, protect coastal environments and strengthen the small-vessel market. We hope this report provides a clear roadmap for advancing hydrogen-powered maritime transportation.

John Rossant
President
Monaco Hydrogen Alliance

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International Taskforce on Hydrogen Mobility in Coastal Areas

In October 2024, the Monaco Hydrogen Alliance, in partnership with ENOWA-NEOM, established the International Taskforce on Hydrogen Mobility in Coastal Areas (ITHCA), which counts among its members some of the leading startups and established companies working on cutting-edge hydrogen technologies to explore collaborative opportunities, discuss challenges, and accelerate the transition to zero-emission marine transport. The first meeting of ITHCA members was convened on the occasion of the Monaco Hydrogen Forum in December 2024.

The present white paper was presented at a special session of the Blue Economy & Finance Forum in Monaco on June 7th 2025. It was authored by Dr. Riccardo Mastini (Director of Research at the Monaco Hydrogen Alliance) with the support of representatives from the International Taskforce on Hydrogen Mobility in Coastal Areas: Mr. Hussain Alzayer (ENOWA-NEOM), Dr. Hervé Gregoire-Mazzocco (ENOWA-NEOM), Dr. James Turner (King Abdullah University of Science and Technology), Ms. Rebecca Sharp (Genevos), Mr. Phil Sharp (Genevos), Mr. Andrea Minerdo (NatPower H), Mr. Marco Vassallo (NatPower H), Mr. Sean Caughlan (Glosten), Mr. Albin Josse (HYNAVAL), Ms. Chloe Zaied (Ephyra), Dr. Pierre Sames (DNV), Mr. Charles Boulanger (INOCEL), Mr. Vincent Maheo (HELION), Mr. Eirik Malterud (Hyrex), Mr. Sumer Daou (Mina Canaan), Mr. Fredrik Thornell (Green City Ferries).

Abbreviations

ABS: American Bureau of Shipping

ABI: AirCarbon Exchange

CCfD: Carbon Contracts for Difference

CCC: IMO Sub-Committee on Carriage of Cargoes and Containers

CH_2: Compressed Hydrogen

CO_2: Carbon Dioxide

CII: Carbon Intensity Indicator

DOE: U.S. Department of Energy

ECA: Emission Control Area

EEDI: Energy Efficiency Design Index

EMSA: European Maritime Safety Agency

ETS: Emissions Trading System

EU: European Union

FCH JU: Fuel Cells and Hydrogen Joint Undertaking

GHG: Greenhouse Gas

H_2ICE: Hydrogen Internal Combustion Engine

IACS: International Association of Classification Societies

IEC: International Electrotechnical Commission

IEA: International Energy Agency

IAPH: International Ports Association

IHS: International Hydrogen Society (implied)

IMO: International Maritime Organization

ISO: International Organization for Standardization

ITF: International Transport Forum

ITTC: International Towing Tank Conference

IWSA: International Windship Association

JDP(s): Joint Development Project(s)

LFZ: Liquid Fuel Zone (implied in context of LH_2 bunkering)

LH_2: Liquid Hydrogen

LNG: Liquefied Natural Gas

MARPOL: International Convention for the Prevention of Pollution from Ships

MEPC: Marine Environment Protection Committee (IMO)

NO_x: Nitrogen Oxides

OIC: Orkney Islands Council

PEM: Proton Exchange Membrane

PSI: Pounds per Square Inch (in pressure context)

RNG: Renewable Natural Gas

SAE: Society of Automotive Engineers

SEEMP: Ship Energy Efficiency Management Plan

SOFC: Solid Oxide Fuel Cell

SO_x: Sulfur Oxide

Technical Analysis

Innovation, Efficiency, and Hydrogen's Maritime Breakthrough

Regulatory Pressure and Sustainable Imperatives

Small maritime vessels, encompassing ferries, yachts, and coastal patrol boats, constitute a pivotal component of regional transportation networks, tourism economies, and maritime security. However, their reliance on conventional diesel-fuelled propulsion systems presents profound environmental challenges. These vessels emit substantial quantities of greenhouse gases, including carbon dioxide (CO_2), as well as nitrogen oxides (NOx), sulfur oxides (SOx), and particulate matter, all of which have significant implications for air and water quality. The accumulation of these emissions exacerbates climate change, contributes to the formation of smog in coastal regions, and increases health risks for communities that depend on maritime industries.

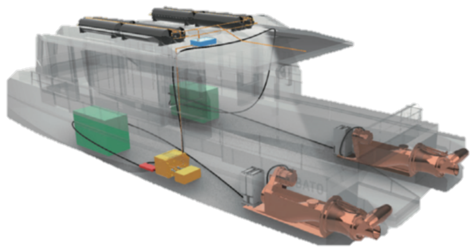
Furthermore, the impact of these emissions extends beyond atmospheric pollution. Nitrogen oxides and sulfur oxides interact with water vapor, leading to acid deposition, which can harm marine biodiversity and corrode critical infrastructure such as docks, ship hulls, and navigation buoys. The particulate matter released by diesel combustion settles on water surfaces, altering the light penetration necessary for marine plants and disrupting delicate aquatic ecosystems. Additionally, the release of unburned hydrocarbons into the ocean creates surface films that impede oxygen exchange, further stressing marine life.

The reliance on diesel engines also increases background underwater noise, a less discussed but equally harmful environmental factor that has adverse effects on critical life functions for a wide range of marine life. The low frequency noise of internal combustion engines can penetrate significant distances underwater and interferes with marine species' communication, breeding behaviour, migration patterns, and predator-prey interactions, particularly for species such as whales and dolphins that rely on echolocation. Increased vessel traffic has been linked to changes in the behavioral patterns of marine life, causing habitat displacement and increased mortality rates.

Moreover, the storage and transport of conventional fuels pose risks of oil spills and fuel leaks, which have immediate and potential long-term repercussions on marine ecosystems. Unlike diesel or heavy fuel oil, which persist in the environment and require extensive remediation efforts, hydrogen dissipates rapidly into the atmosphere when leaked, making it a safer alternative from an environmental standpoint. As concerns regarding the ecological footprint of small maritime vessels grow, transitioning to zero-emission propulsion technologies becomes an imperative rather than an option. Hydrogen as marine fuel, with its zero-emission profile and high energy density, stands as a transformative solution that aligns economic viability with environmental responsibility.

These emissions are not merely localized concerns; they have cascading global consequences, contributing to atmospheric warming, respiratory health deterioration, and marine ecosystem degradation. Given that approximately 40% of the global population resides in coastal regions—areas that simultaneously support nearly 80% of marine biodiversity—the imperative for mitigating these environmental impacts cannot be overstated.

The combustion of diesel fuel within maritime engines is a principal contributor to air quality deterioration in port cities and coastal zones, exacerbating conditions such as asthma, cardiovascular diseases, and other respiratory ailments. Moreover, the sulfur content in marine fuels, even after the implementation of regulatory sulfur caps, continues to play a role in acid rain formation, negatively affecting both terrestrial and aquatic ecosystems. Additionally, the absorption of anthropogenic CO_2 by the world's oceans is accelerating ocean acidification, which has profound implications for marine biodiversity. Increased acidity undermines calcifying organisms, including corals, shellfish, which serve as foundational species within marine food webs, and importantly marine calcifying phytoplankton, which plays a major role in the biogeochemical cycles and in the regulation of the global climate. The erosion of these ecosystems threatens commercial fisheries, biodiversity stability, and overall oceanic health.



Credit: Hynaval

Hydrogen-powered vessels not only address these concerns but also provide ancillary environmental benefits. The transition to hydrogen can lead to reduced underwater noise, mitigating disturbances to marine ecosystems. Furthermore, advancements in hydrogen storage and distribution technology, such as dedicated pipelines, can enable more efficient deployment of this fuel, reducing dependency on large fossil fuel supply chains that exacerbate environmental harm. The integration of green hydrogen—produced through electrolysis powered by renewable energy—can eliminate almost entirely life cycle emissions from a well-to-wake perspective.

The maritime sector is undergoing an unprecedented regulatory transformation aimed at curbing emissions and fostering sustainability. In April 2025, the International Maritime Organization (IMO) approved the draft legal text for what is now the first industry-wide Net-Zero Framework, combining mandatory CO_2 emissions limits with a global GHG pricing mechanism. A key element of this regulatory breakthrough is represented by a market-based instrument—setting a carbon price to incentivize lower-carbon fuels and technologies— that will be formally adopted at an extraordinary MEPC session in October 2025 and enter into force in January 2027. These policies signal a decisive shift in maritime regulatory frameworks, necessitating industry-wide adoption of alternative propulsion technologies. Given the pace of regulatory tightening, industry stakeholders must proactively seek compliance strategies to avoid economic penalties and reputational risks.

Credit: MBM-P01 – Hydrogen Tender

In addition to global directives, regional regulatory frameworks are intensifying pressure on vessel operators to decarbonize. The European Union's Emissions Trading System (ETS) has been expanded to incorporate maritime emissions, imposing financial liabilities on operators who continue to utilize fossil fuel-based propulsion. And the European FuelEU Maritime Regulation stipulates an increasing use of low GHG-intensity fuels by ships in EU waters and voyages into and out of EU ports. Norway has set an ambitious precedent by mandating that all ferries operating within its fjords achieve zero-emission status by 2026, demonstrating the feasibility of wide-scale hydrogen and battery-electric adoption. Similarly, California's Advanced Clean Fleets Rule is catalyzing the transition to zero-emission maritime transport by requiring port and ferry operators to adopt cleaner alternatives within a defined timeframe. Other jurisdictions are following suit, with policy instruments such as carbon pricing, emissions caps, and direct investment in hydrogen refueling infrastructure shaping the decarbonization trajectory.

Economic incentives are also shaping the trajectory of decarbonization efforts. Governments and international bodies are deploying subsidies, grants, and tax incentives to facilitate the widespread adoption of green technologies. Programs such as the European Green Deal, which earmarks funding for sustainable transport solutions, and various national hydrogen strategies that support infrastructure development, provide critical financial backing for vessel operators navigating this transition. Beyond governmental efforts, private investments are increasing, with venture capital and large corporations allocating significant resources to hydrogen fuel technology development and deployment.

While larger maritime corporations have the financial and technical capacity to invest in the development and deployment of hydrogen and battery-electric technologies, smaller operators often encounter substantial economic and infrastructural barriers. Recognizing these constraints, investment in workforce development, including specialized training programs for hydrogen technology maintenance and operations, will be essential in ensuring a smooth industry-wide shift. Collaboration between the private sector, regulatory agencies, and research institutions will further bolster the practicality of hydrogen adoption in maritime transport, ensuring long-term success in decarbonizing small vessel operations.

Credit: Poseidon, Inocel

Green Hydrogen as a Key Enabler to Maritime Decarbonisation

The imperative to transition toward sustainable propulsion technologies in the maritime sector has never been more pronounced. With intensifying regulatory constraints and escalating environmental concerns, identifying an energy source that combines efficiency, scalability, and ecological responsibility is paramount. While battery-electric systems have proven effective for in-port applications and short ferry crossings—benefiting from higher energy-conversion efficiencies on paper—they remain constrained by limited energy density, payload penalties, operational range, and the nascent state of maritime charging infrastructure. By contrast, hydrogen fuel cell technology, despite somewhat lower conversion efficiency, delivers higher gravimetric energy density, extended range, faster refueling, and substantial environmental benefits, making it the preferred solution for longer-distance vessels and a key enabler of comprehensive maritime decarbonization.

Hydrogen fuel cells are poised to play an indispensable role in maritime decarbonization, particularly within coastal ferry networks and regional shipping routes. The convergence of technological innovation, regulatory enforcement, and economic incentives underscores the strategic superiority of hydrogen propulsion over both conventional fossil fuels and battery-electric alternatives. Offering superior energy density, rapid refueling times, and seamless integration with hybrid propulsion architectures, hydrogen represents a scalable and operationally viable solution for the maritime industry.

The continued advancement of hydrogen storage solutions, fuel cell efficiency enhancements, and electrolysis cost reductions will further consolidate hydrogen's competitive position within the maritime sector. Sustained collaboration among governmental agencies, maritime industry leaders, and research institutions will be critical in driving infrastructure expansion, cost optimization, and widespread commercial adoption. By spearheading this transition, the maritime industry stands to achieve a transformative shift toward sustainability, aligning with international emissions reduction mandates while maintaining the operational reliability essential for global commerce and transportation.

Environmental factors such as temperature, humidity, and saltwater exposure play a significant role in the performance and longevity of hydrogen systems, particularly in marine applications. While modern advancements have minimized many of these impacts, certain challenges remain that must be carefully managed to ensure reliable and efficient operation.

Humidity generally has a positive effect on hydrogen fuel cells. Fuel cells require a certain level of humidity to prevent the drying out of the membrane, which is critical for maintaining ionic conductivity between the anode and cathode. Proper moisture levels help sustain optimal electrochemical reactions, improving efficiency and longevity. However, excessive moisture could lead to condensation-related challenges in some system components, requiring careful humidity control mechanisms. Marine-certified fuel cells are typically not significantly impacted by humidity, as their internal systems regulate moisture levels effectively.

High temperatures, on the other hand, are generally manageable, especially in maritime environments where water can be used for cooling. However, in hotter climates, lower oxygen density in the air may necessitate larger compressors to maintain optimal fuel cell performance. Most marine-certified fuel cells are designed to operate within a standard temperature range of approximately -10°C to +45°C. Built-in cooling systems and thermal management strategies help regulate fuel cell performance, ensuring stable operation despite ambient temperature variations.

Saltwater exposure is one of the most critical environmental challenges for hydrogen systems in marine applications. Salty air can accelerate the corrosion of metallic components within the fuel cell system, potentially reducing the lifespan of key parts such as metallic plate stacks. In contrast, graphite plate stacks, such as those used in Ballard or Helion fuel cells, demonstrate higher resistance to salt-induced degradation.

To mitigate corrosion risks, hydrogen systems in marine environments require the use of corrosion-resistant materials such as 316L stainless steel, which prevents hydrogen embrittlement and withstands the harsh marine environment. Additionally, advanced air filtration and enclosure designs help shield sensitive components from direct saltwater exposure, prolonging the durability of the system. Fuel cells are often installed inside protective compartments where both ventilation and oxidation air are filtered to reduce contamination from salty air.

Credit: X Shore - Eelex 8000

The Limitations of Battery-Electric Propulsion

Performance considerations further influence the choice between hydrogen and batteries. Hydrogen fuel cells are particularly well-suited for vessels requiring consistent power output over long durations, as fuel cells operate at peak efficiency under stable loads. This makes them an ideal choice for applications such as high-performance vessels and research ships that require stable and reliable power delivery. Stable loading also significantly extends the lifetime potential of the fuel cell with respect to land-based applications which are more dynamic. Additionally, hydrogen powertrains offer a distinct advantage in terms of refueling speed compared to battery charging. The ability to quickly refuel with hydrogen, particularly liquid hydrogen, minimizes downtime and enhances operational efficiency. Battery-electric systems, however, remain advantageous for applications where high efficiency, lower capital expenditure, and simplified operational requirements are prioritized.

The deployment of battery-electric propulsion in the maritime domain is fraught with substantial technical and logistical impediments. Chief among these limitations is energy density. Lithium-ion marine battery systems offer energy densites in the range of 100 - -200 Wh/kg, a stark contrast to the 1,200-1,500 Wh/kg now achievable through fuel cells combined with compressed hydrogen storage. This disparity severely restricts the operational range of battery-electric vessels. A 200-passenger ferry reliant on battery-electric propulsion is constrained to a maximum range of approximately 35 nautical miles before necessitating an extensive recharging cycle. Conversely, hydrogen-powered vessels can readily exceed 150 nautical miles under comparable energy constraints. Furthermore, liquid hydrogen (LH_2) propulsion technology pushes these boundaries significantly, with prototype vessels demonstrating an impressive range of up to 1,000 nautical miles, rendering them particularly well-suited for inter-island connectivity and extended coastal-haul routes.

Credit: Hydrogen Hydro-Foiling Catamaran, American Magic

One of the most defining differences between hydrogen fuel cells and electric batteries is range. Battery-electric propulsion is often suitable for short-range applications, particularly when frequent charging opportunities are available. Hydrogen's higher energy density compared to batteries is a key factor in its suitability for vessels requiring extended autonomy. This makes hydrogen particularly attractive for applications where recharging times are impractical or where the vessel operates in remote locations with limited electrical infrastructure. Hydrogen fuel cells offer a significant weight advantage over battery systems, particularly for vessels requiring extended range. Batteries tend to become impractically heavy as energy storage requirements increase, making hydrogen a more favorable choice for larger vessels. Hydrogen powertrains, depending on vessel requirements, are often several times lighter than equivalent all-battery systems, which directly impacts vessel efficiency and performance. However, while hydrogen is advantageous in terms of weight, it presents challenges in terms of volume. Storage space for hydrogen tanks must be carefully considered in the vessel's architectural design.

The logistical inefficiencies of battery-electric propulsion are further magnified by the inadequacy of high-capacity charging infrastructure at maritime ports. The recharging duration for a standard 500 kWh battery ranges between four and six hours, an untenable interruption for commercial maritime operations requiring high-frequency scheduling. In contrast, hydrogen refueling for an equivalent energy can be completed within a 10–15 minute window, a duration closely mirroring the efficiency of traditional fossil fuel bunkering, thereby ensuring minimal downtime and uninterrupted service continuity. Additionally, hydrogen fuel cell technology permits modular refueling strategies, allowing vessels to refuel at multiple points along their route without necessitating prolonged operational interruptions.

Credit: Maserati Tridente

Hydrogen Fuel Cells as the Cornerstone of Maritime Innovation

Unlike internal combustion engines, which emit both carbon dioxide and nitrogen oxides—major contributors to coastal air quality degradation—hydrogen fuel cell systems produce zero direct emissions and operate with far lower noise and vibration levels. Proton Exchange Membrane (PEM) fuel cells, already proven in several in-service vessels, deliver net energy conversion efficiencies of 50–60%—substantially higher than even optimally tuned combustion engines—while their modular architecture can be scaled from kilowatt- to megawatt-class powerplants with integrated redundancy. This scalability ensures each fuel cell stack runs close to its most efficient operating point, providing consistent, high-performance propulsion under variable maritime conditions (including high-power demands and adverse weather), faster refueling, and robust environmental benefits—making PEM fuel cells the leading choice for long-range and fully decarbonized small vessels.

The versatility of hydrogen storage and distribution mechanisms further bolsters its maritime viability. Hydrogen can be stored in a compressed gaseous form at 350–700 bar for short-range applications or as liquid hydrogen (LH_2) at cryogenic temperatures of -253°C for long-haul maritime operations. Moreover, hybrid vessel architectures, integrating hydrogen fuel cells with auxiliary battery-electric systems, offer an optimal synergy, balancing baseline power demands while efficiently managing peak energy requirements. This hybrid approach enhances energy redundancy, ensuring vessel operability in diverse maritime contexts and mitigating risks associated with single-system failures.

Credit: Candela C8

Hydrogen as a Fuel for Marine Internal Combustion Engines

As a fuel (i.e. once it is made available to a propulsion system and assuming all safety and practicality issues associated with its distribution and storage can be safely handled) hydrogen is in many ways an ideal fuel for an internal combustion engine (ICE), although it is not without its drawbacks. For marine engines perhaps the first demerit is that hydrogen is best suited to spark-ignition ICEs, although it can be used in diesel-type engines, with modifications. This SI suitability stems from the fact that it has a high resistance to autoignition, enabling high compression ratios (and thus efficiency), a very high laminar burning velocity, and rapid mixing characteristics. However, major problems for some SI engines are its low ignition energy, which gives rise to backfire in ICEs where the fuel is introduced to the airstream outside of the combustion chamber, and its low volumetric energy density, which causes a reduction of specific power unless countermeasures are taken (although it is likely that marine hydrogen ICEs will have higher specific power than their diesel counterparts anyway).

Both of the above disadvantages can broadly be overcome using direct fuel injection, and such systems are being developed for heavy-duty (HD) on- and off-road engines for land use. Further technologies such as pre-chamber ignition and the use of cooled exhaust gas recirculation (EGR) and/or water injection to control abnormal combustion are also being heavily researched, and can leverage previous work for fossil-fuelled SI engines. These technologies also help to address the only significant issue in terms of H2ICE operation in tightly-controlled emissions areas and ECAs, that of the emission of oxides of nitrogen (NOx). These emissions arise because the adiabatic flame temperature of hydrogen is very high, oxidizing nitrogen in the combustion process, and this especially causes significant NOx production at close to stoichiometric (chemically-correct) conditions; the high temperature also increases heat loss (coupled with hydrogen's very small quenching distance, which allows the flame to burn close to the combustion chamber walls). Fortunately, the extremely high laminar burning velocity referred to above also enables extreme charge dilution, which in turn reduces the flame temperature and NOx formation and furthermore increases efficiency directly through reduced heat rejection. The diluents used can take the form of excess air, cooled EGR, or water (which in turn can readily be condensed from the exhaust stream, removing challenges with desalinating sea water), or a combination. The result is a need for minimum after treatment, with all the technologies that may be needed for this being well understood in mass production for diesel and SI engines anyway. Note that in H2ICEs some CO2 emissions will result either directly from lubricating oil consumption or indirectly from the use of urea-based selective catalytic reduction systems. The level of these will not be great though, and for road transport the levels of CO2 emissions are easily within the limits of recent EU on-road zero-emissions HD legislation (in terms of gCO2/tonne-km or gCO2/passenger).

Having said all of the above, one can now answer a more fundamental question: even if H2ICEs can be made emissions compliant, why would one want to employ them in marine HD applications versus a fuel cell? There are two main reasons depending on the type of fuel cell one is drawing a comparison with. Firstly, ICEs are obviously cheap to produce, and dominant in transport due to this and the current levels of reliability, durability, and operational knowledge. At present levels of technology readiness, HD engines are significantly more durable than any fuel cell. Secondly, the rate of load change of ICEs is orders of magnitude better than for the solid oxide fuel cell (SOFCs) types which, although they can be made extremely highly efficient, have some significant operational challenges as a result. Nevertheless, SOFCs do offer a very relevant area of study for marine applications when there is no need for stop and start, and there could be some very beneficial synergies when they are combined with H2ICEs in an integrated system.

Important considerations need to be addressed in relation to the operating cost of a vessel using H2ICE operating at 35-40% average efficiency, versus a PEM FC system operating at 50-55% efficiency. For commercial vessels, typically operating at circa 4000 hours per year, operational cost is weighted much higher with respect to CAPEX, and due to the fuel saving, fuel cell vessels pay themselves off after 2 years, providing TCO benefit beyond this in relation to H2ICE. However for applications such as recreational vessels, H2ICE could present an overall cost benefit where the annual usage is much lower. The conversion efficiency between the two technologies also dramatically affects the storage volume of hydrogen onboard a vessel, with a H2ICE vessel requiring 35-40% more volume than a PEM FC vessel travelling the same distance. Considering that storage volume is often an important limiting factor for hydrogen vessels, this factor could be highly influential regarding the choice between the two technologies.

Credit: NatPower H

Looking to the future, marine H2ICE propulsion systems could be made yet more efficient by employing techniques to extract the physical energy of storage of hydrogen on a ship. Whether it is stored as a pressurized gas or cryogenically, the fact that an equivalent of 10-15% of the chemical energy is in physical form when stored is sufficient inducement to warrant further investigation. This could perhaps most beneficially use the waste heat from an ICE, but could also be applied to fuel cells or combined powerplants. Whatever the long-term future, H2ICEs definitely hold a large appeal in HD applications, and undoubtedly new concepts will emerge to further optimize such engines in the marine environment.

The Emergence of Floating Hydrogen Refueling Hubs

The proliferation of hydrogen-powered vessels necessitates an equally robust expansion in fueling infrastructure. While terrestrial hydrogen refueling stations are progressively being established in key maritime hubs, an innovative paradigm—floating hydrogen production platforms—is set to redefine hydrogen accessibility. These offshore installations harness wind and solar energy to power electrolysis, generating green hydrogen on-site and facilitating its direct integration into maritime corridors.

Floating hydrogen hubs present a range of strategic advantages. Their offshore placement optimizes renewable energy utilization, ensuring maximal electrolytic efficiency. Additionally, deep-sea temperature stability, ranging between 4–10°C, enhances thermal regulation within electrolyzer systems, mitigating energy losses. Moreover, these floating platforms exhibit intrinsic mobility, allowing them to be dynamically repositioned in alignment with high-density shipping routes and renewable energy hotspots, thereby optimizing logistical efficiency and cost-effectiveness. The dynamic deployment of floating refueling stations is particularly advantageous for high-traffic ferry routes and offshore transport networks that lack onshore hydrogen infrastructure.

The implementation of floating refueling stations also mitigates land-based infrastructural constraints. Many coastal urban centers lack the spatial availability required for large-scale hydrogen storage and distribution networks. Offshore hydrogen platforms provide a scalable, adaptable alternative, ensuring that hydrogen-powered vessels remain operationally autonomous without reliance on extensive land-based refueling networks. Additionally, these platforms facilitate integration with offshore wind farms, leveraging excess renewable energy for hydrogen production, thereby enhancing the sustainability of the overall maritime energy ecosystem.

Credit: Arthemis Technologies

Economic Analysis

Cost, Capital, and the Hydrogen Maritime Revolution

Comparative Analysis of Initial Capital Costs

The initial capital costs for hydrogen-powered vessels remain substantially higher than those for conventional diesel-powered or electric battery systems, primarily due to the immaturity of hydrogen fuel cell technology and limited economies of scale. conventional diesel-powered vessels benefit from mature supply chains, standardized equipment, and well-established maintenance procedures, resulting in lower initial capital costs. Electric battery-powered vessels, though facing high battery costs, have seen rapid reductions in pricing due to advancements in lithium-ion technology driven by the automotive industry. However, electric battery systems face challenges in maritime applications due to the sheer size and weight required for long-range operations.

Hydrogen fuel cells rely on costly materials such as platinum catalysts, and their manufacturing processes are not yet optimized for mass production. The high upfront investment stems from several key factors, including the cost of hydrogen fuel cell technology, storage infrastructure, and refueling stations. Hydrogen fuel cells, while offering high efficiency and zero emissions, are still manufactured at relatively low volumes, making economies of scale challenging to achieve. Materials such as platinum, used in fuel cell catalysts, add to the cost burden, though ongoing research is exploring cost-effective alternatives including platinum-free catalysts.

Credit: Inocel

Hydrogen storage and refueling infrastructure further exacerbate upfront expenditures. Liquid hydrogen (LH_2) storage demands cryogenic tanks with vacuum insulation and boil-off gas recovery systems. In contrast, diesel infrastructure is globally established, with refueling networks and engine supply chains offering cost efficiencies. However, hydrogen's cost trajectory is promising. Despite the steep initial costs associated with hydrogen-powered vessels, several factors suggest a downward trend in pricing. The ongoing expansion of hydrogen infrastructure, government subsidies, and advancements in fuel cell manufacturing processes are expected to drive down costs over time. Analogous to solar photovoltaic systems, which saw a 90% price drop between 2000 and 2020, hydrogen fuel cell costs are projected to decline by 40–60% by 2030 as production scales up. Recent projects, such as Norway's MF Hydra ferry and Japan's Suiso Frontier carrier, demonstrate incremental cost reductions through modular fuel cell designs and shared infrastructure.

Despite the high upfront costs, some stakeholders argue that hydrogen fuel cell systems can be cost-competitive under certain conditions. If used as a primary power source rather than a range extender, hydrogen propulsion may be more economical than batteries and only about 40% more expensive than diesel. However, this is highly dependent on system design and operational needs. One of the main cost differentiators between hydrogen and batteries is the necessity for fuel tanks. Batteries, by contrast, eliminate the need for fuel storage, making them more straightforward and cost-effective for short-range applications. However, for vessels requiring longer range and higher energy densities, hydrogen still presents advantages despite the higher initial costs.

Credit: Piriou

Comparative Analysis of Operational Costs

Hydrogen fuel costs currently exceed those of diesel due to limited production capacity and distribution networks. Green hydrogen, produced via electrolysis using renewable energy, remains expensive, though production costs are projected to decline as electrolysis efficiency improves and renewable energy prices drop. By 2030, the cost of green hydrogen is expected to reach parity with diesel in some regions, particularly where abundant renewable resources drive down electricity costs.

Maintenance costs for hydrogen-powered vessels are generally 20-30% lower than for diesel-powered ships. Hydrogen fuel cells have fewer moving parts than internal combustion engines, reducing mechanical wear and the frequency of maintenance interventions. For example, the Corvus Energy fuel cell system used in the HySeas III ferry requires only biannual inspections, compared to quarterly servicing for diesel engines. Hydrogen systems, while initially costly, benefit from longer lifespans (15–20 years) and lower degradation rates.

However, some maintenance challenges remain, particularly concerning hydrogen storage and delivery systems. Cryogenic storage for LH_2 requires periodic inspections and specialized handling procedures. Additionally, fuel cell stacks degrade over time, requiring replacement every 10-15 years, which adds to long-term operational costs. Operational efficiency hinges on fuel cell efficiency, which currently averages 15% better than diesel engines. However, over the whole value chain, efficiency losses occur during hydrogen compression, storage, and distribution, which must be factored into overall energy calculations. Advances in proton-exchange membrane (PEM) technology, such as Toyota's Mirai-derived stacks, promise efficiencies exceeding 65% by 2030. Variability in hydrogen supply chains also impacts costs. Regions with integrated renewable hydrogen hubs, like Australia's Hydrogen Valley, enable "production-to-propulsion" models that minimize transportation expenses.

The availability of refueling stations remains a key challenge. Limited hydrogen bunkering infrastructure increases operational complexity and costs, particularly for long-haul shipping. Mobile or offshore refueling solutions (e.g. floating hydrogen production platforms) could mitigate some of these issues, but widespread implementation remains years away. Also weather and operational profiles further influence costs. Hydrogen vessels operating in cold climates benefit from reduced boil-off losses, while tropical regions require additional energy for refrigeration. Route optimization tools, such as Siemens' NaviPlan, can reduce fuel consumption by 15% through dynamic speed adjustments and weather routing.

Regional energy prices also influence hydrogen operational costs. Countries with low renewable electricity prices and favorable policy frameworks will achieve cost-competitive hydrogen faster than those reliant on fossil-fuel-based hydrogen production. Consequently, vessel operators must carefully evaluate regional hydrogen supply chains when planning fleet transitions.

Credit: Ephyra

Examination of Funding Sources, Grants, and Incentives

Global funding mechanisms are pivotal in bridging the capital gap for hydrogen adoption. For example, the European Union, through Horizon Europe's Zero Emission Waterborne Transport (ZEWT) initiative, has earmarked approximately €500 million, of which around €75–100 million has already been allocated to hydrogen and fuel-cell technologies for maritime applications. The EU's Hydrogen Bank aims to reduce investment risks by providing subsidies for green hydrogen production. Similarly, in the United States, the Department of Energy's Hydrogen and Fuel Cell Technologies Office (HFTO) offers grants and loan guarantees for hydrogen-related projects, including maritime applications. Additionally, national and regional policies such as Norway's NOx Fund, Japan's Green Innovation Fund, and South Korea's Hydrogen Economy Roadmap provide financial backing for hydrogen fuel cell deployment in shipping.

Public-private partnerships (PPPs) are accelerating infrastructure deployment. Private-sector engagement is also growing, with major energy companies and shipbuilders investing in hydrogen vessel pilot projects. Public-private partnerships, such as the EU's H2MARINE initiative, demonstrate the role of collaborative funding in scaling up hydrogen adoption. The Port of Rotterdam's H2Gate initiative, a collaboration between Shell, Mitsubishi, and the Dutch government, is investing €100 million to establish a hydrogen bunkering network by 2025. Carbon contracts for difference (CCfD), such as those under Germany's H2Global scheme, further de-risk investments by guaranteeing long-term price stability for green hydrogen. Additionally, classification societies like Lloyd's Register and Bureau Veritas are offering reduced certification fees for hydrogen-compliant vessels, incentivizing early adopters.

Anticipated regulations, such as the International Maritime Organization's (IMO) 2050 net-zero targets and stricter local air quality rules (e.g., California's CARB guidelines), will disproportionately affect diesel-powered vessels. Early adopters of hydrogen avoid costly retrofits or operational disruptions. Carbon pricing and emissions trading schemes further bolster the economic case for hydrogen. In jurisdictions with stringent carbon regulations, hydrogen-powered vessel operators can benefit from reduced taxes and the ability to sell carbon credits, partially offsetting the high capital costs. For instance, a hydrogen ferry displacing 500 tons of CO2 annually could earn €15,000–€30,000 in credits (at current EU ETS prices of €60–€90/ton). As carbon prices rise, this revenue stream could offset a significant portion of fuel costs. These incentives make hydrogen an increasingly attractive alternative to traditional fossil fuels, particularly in regions with aggressive decarbonization targets.

Voluntary markets, on the other hand, cater to corporations and individuals seeking to offset emissions voluntarily, often to meet ESG targets. Luxury yacht owners, for instance, could market their vessels as "carbon-neutral" by retiring credits equivalent to residual lifecycle emissions, such as those from hydrogen production or vessel construction. To monetize carbon credits, operators must first quantify emissions reductions by comparing a hydrogen vessel's performance against a conventional baseline. For example, a ferry transitioning from diesel to hydrogen could avoid approximately 500 tons of CO_2 annually, assuming annual diesel consumption of 200,000 liters. Projects must then be certified through recognized standards such as Verra's Verified Carbon Standard or the Gold Standard, using methodologies tailored to maritime applications, such as "Fuel Switching for Marine Vessels." Independent third-party verification ensures the integrity of emission reductions, after which credits can be listed on exchanges like CBL or AirCarbon Exchange or sold directly to buyers.

Credit: Ephyra

Beyond direct revenue, carbon credits confer strategic advantages. Operators of luxury yachts can leverage carbon-neutral certifications to attract eco-conscious clients, with charter companies reporting a 20–30% premium for sustainable offerings. Corporate partnerships also emerge as opportunities; tourism firms or cruise lines seeking to decarbonize supply chains may contract with hydrogen vessel operators for "insetting," where credits directly offset the buyer's maritime logistics emissions. A 2023 survey by DNV found that 65% of high-net-worth individuals are willing to pay a premium for low-carbon yachts. Hydrogen vessels cater to this demand, enabling operators to command higher charter rates or resale values.

Challenges exist, however. Projects must demonstrate 'additionality', proving emissions reductions would not have occurred without carbon finance. Vessels using green hydrogen (produced via renewables) face fewer scrutiny risks than those relying on grey hydrogen (derived from fossil fuels). Upfront costs for verification, certification, and registry fees can be a barrier, though grants like those from the EU's Innovation Fund may alleviate expenses. Market volatility also poses risks, as credit prices fluctuate with policy shifts and demand. Long-term contracts with credit buyers can mitigate this uncertainty.

Credit: Alpine

Additional hurdles include the limited availability of hydrogen refueling hubs, often forcing operators to use expensive mobile units or make lengthy detours to equipped ports. Storing hydrogen onboard—whether under high pressure or as a cryogenic liquid—requires design modifications that raise capital and maintenance costs. Strict safety regulations and specialized crew training further add to operational expenses and insurance premiums. Yet small vessels like harbor shuttles and survey boats, which benefit most from quick refueling and near-silent propulsion, offer an ideal proving ground. Coordinated pilot projects and public–private partnerships can share risks and drive the development of shared refueling infrastructure, ultimately smoothing the path for wider uptake of zero-emission hydrogen workboats.

ITHCA stakeholders point to a lack of clear long-term strategies for hydrogen adoption, with organizations reluctant to commit due to high regulatory and market uncertainties. This reluctance limits investment in long-term projects, slowing industry progress. Addressing this requires a shift from fragmented, independent initiatives to a more integrated approach involving shared strategies and commitments. One of the key bottlenecks in advancing hydrogen mobility is the insurance sector, which is critical in de-risking new technologies. If insurers actively support hydrogen projects, it could provide vessel operators with greater confidence to invest in this transition. Additionally, strengthening safety regulations and conducting extensive testing can help build trust in hydrogen as a viable maritime fuel.

Collaboration between vessel operators, solution providers, and port authorities should be strengthened to create cohesive hydrogen ecosystems. This would not only provide clarity for individual stakeholders but also reduce risk by ensuring that all elements of the hydrogen value chain are progressing in tandem. Stakeholders suggest that government-led Hydrogen Hubs, such as those being developed in the U.S., could serve as a catalyst for such collaborative efforts if they are executed effectively.

To break the impasse, stakeholders should rally around unified, long-term hydrogen roadmaps that marry regulatory targets with market incentives and infrastructure build-out. Governments can de-risk investments through loan guarantees, tailored insurance products, and phased uptake mandates, while classification societies and insurers align on harmonized safety standards and premium discounts for early adopters. Embedding hydrogen mobility in clear policy frameworks and carbon-pricing mechanisms will signal stability, reduce technology risk, and unlock private capital.

Regional 'Hydrogen Hubs'—where port authorities, shipbuilders, energy suppliers, and tech firms co-invest in shared refueling networks, R&D facilities, and training centers—can achieve economies of scale and pool risks. Targeted pilot corridors (e.g., ferry links or coastal freight routes) will serve as proving grounds to refine operations, validate safety protocols, and demonstrate cost reductions. As these ecosystems mature, cumulative learning and shared infrastructure will drive down both capital and operational costs, paving the way for hydrogen's broader adoption across the maritime sector.

Credit: Glosten

Regulatory Analysis

Policies for a Hydrogen-Ready Maritime World

Safety Challenges and Risk Management

One of the primary challenges of hydrogen-powered small vessels is ensuring safety. Hydrogen, while a clean and efficient fuel, is highly flammable and requires specialized storage and handling protocols to prevent leaks and explosions. The maritime industry must develop and certify technologies that can safely store and usehydrogen under the demanding conditions of maritime operations. This includes advanced storage tanks that can withstand the rigors of rough seas and very low temperatures (in case of liquid hydrogen), as well as the implementation of stringent safety protocols to mitigate the risks associated with hydrogen's high flammability and low temperature and, thus, to ensure safe operations.

Fuel cell technology, which is central to hydrogen propulsion, also presents safety challenges. Fuel cells must demonstrate reliability and safety under maritime conditions, which can include exposure to saltwater, high humidity, and extreme temperature fluctuations. The industry must work closely with classification societies to develop and certify fuel cell systems that meet these stringent safety requirements. This involves not only the design and testing of the fuel cells themselves, but also the integration of these systems into the overall vessel design and propulsion systems to ensure that they operate safely and efficiently in a maritime environment.

A critical issue raised by ITHCA stakeholders is the perception of hydrogen as a high-risk fuel. Authorities often view hydrogen as a significant safety concern, leading to an approach that is both non-coordinated and excessively restrictive. This over-reaction can slow down the deployment of hydrogen technologies, creating barriers to widespread adoption. The comparison to LNG was made, with stakeholders noting that the over-cautious regulatory stance on LNG similarly delayed its widespread use in the maritime industry. The fear is that hydrogen may follow the same prolonged trajectory before reaching full acceptance and implementation.

ITHCA stakeholders also highlight that stringent safety standards, while critical, often lead to increased costs and delays in certification. Shipyards frequently face challenges when manufacturers fail to certify components like fuel cells, forcing them to either wait for certification or seek alternatives—both of which inflate costs and timelines. These financial burdens can deter investment in hydrogen technology, particularly for smaller operators. Additionally, the lack of standardized certification pathways for hydrogen components exacerbates these challenges, requiring case-by-case evaluations that further slow progress.

Risk mitigation is a critical component of the certification and classification process for hydrogen-powered vessels. Manufacturers and classification societies must work together to conduct thorough risk assessments that focus on hydrogen storage, fuel cell systems, and overall vessel safety. These assessments help identify potential hazards and develop mitigation strategies that can be integrated into the vessel design and operation.

Policy Recommendations

- Establish mandatory safety certification programs for hydrogen storage systems and fuel cells, aligned with ISO 19882 and IEC 62282 standards, to ensure uniformity in maritime applications.
- Fund R&D initiatives to develop hydrogen-compatible materials for storage tanks and fuel cells that withstand maritime conditions (e.g., saltwater corrosion, temperature extremes).
- Develop a single risk-assessment process—created together by class societies (e.g. DNV, Lloyd's Register), industry and national authorities—that standardizes how we evaluate risks for hydrogen-powered small vessels, highlights where countries apply the IMO's alternative design rules differently, incorporates lessons from current harmonization projects, and is updated regularly so approvals are consistent everywhere.
- Launch public-private partnerships to pilot hydrogen-fuelled ships in controlled maritime environments, with findings used to update IMO guidelines.
- Develop safety procedures for multiple fuel (e.g., heavy fuel oil vs. gaseous hydrogen, liquid hydrogen, ammonia, synthetic diesel, methanol etc.) bunkering operations at a dedicated port.

Regulatory Gaps and Standardization Challenges

Another significant challenge is the absence of specific mandatory international regulations for hydrogen power generation systems in the maritime industry. While existing IMO rules were developed for traditional diesel propulsion, the IMO's CCC sub-committee is preparing interim guidelines for hydrogen as a marine fuel—due September 2026 and subject to MSC approval—which, although voluntary, are expected to be widely adopted until formal regulations come into force. In the meantime, major EU classification societies—Lloyd's Register, Bureau Veritas and DNV—have already published requirements for the integration of hydrogen storage and PEM fuel-cell systems aboard classified vessels, helping to steer manufacturers through the current regulatory uncertainty.

The absence of standardized components and systems for hydrogen power gene rationfurther complicates the classification process. Unlike traditional propulsion systems, which have well-established standards and certification pathways, hydrogen power generation systems require a case-by-case assessment. This lack of standardization—common for any emerging technology—adds complexity and cost to classification but can also help manufacturers protect their IP; if every aspect were fully standardized, it would be cheaper and easier for competitors to produce knock-offs quickly.

ITHCA stakeholders emphasize that regulations are developed reactively, lagging behind technological advancements. This disconnect can stifle innovation, as missing mandatory regulations---based by hydrogen's assessedrisks---delay deployment. Comparisons to LNG's adoption trajectory underscore concerns that hydrogen may face similar delays unless industry is not pushing for faster piloting. Collaborative efforts between industry and regulators are critical to co-developing adaptive frameworks that balance safety with feasibility.

Policy Recommendations

- Convene a coalition of industry stakeholders—manufacturers, classification societies, and standards organizations—to develop a universal component standardization roadmap for hydrogen propulsion systems (e.g., tanks, valves, sensors) that minimizes case-by-case evaluations.
- Introduce tax incentives for manufacturers adhering to pre-certified hydrogen components, accelerating compliance.
- Recommend that flag States adopt the IMO's interim hydrogen guidelines—effective early 2027—alongside classification society rules (e.g., DNV's Hydrogen as a Fuel) until global standards are finalized.
- Develop electric and hydrogen powertrain certification programs in parallel to achieve a full hybrid system certification and type approval.

Collaboration and Industry-Stakeholder Engagement

Collaboration between manufacturers and classification societies is crucial for the development of practical hydrogen-specific rules. By working closely with classification societies such as Lloyd's Register, Bureau Veritas, or DNV, manufacturers can help shape emerging standards and ensure that they accurately address the risks and technical aspects of hydrogen-powered propulsion. This collaborative approach is essential for creating a regulatory framework that supports the safe and efficient deployment of hydrogen-powered vessels. Furthermore, cross-industry learning could also represent a path forward worth considering. For instance, adopting established protocols from other industries, such as the automotive sector's SAE J2601 fueling standards, could accelerate regulatory alignment. These existing frameworks provide proven safety benchmarks, reducing the need to develop entirely new maritime-specific standards.

ITHCA stakeholders highlight the importance of collaboration between regulatory bodies and industry representatives in developing these emerging standards. Such collaboration ensures that regulations do not become overly restrictive or disconnected from practical industry needs. The need for a balanced approach---one that maintains safety while allowing for innovation---is a recurring theme in stakeholder perspectives. Additionally, the regulatory approach varies by region. For example, the U.S. Coast Guard generally aligns its requirements with IMO standards and other industry safety norms, although it is not clear that it applies any uniquely different rules. More broadly, flag States have the authority to adopt their own approaches—so long as they don't conflict with existing mandatory obligations—which means vessel designers, builders and operators must still navigate a patchwork of national interpretations and requirements.

Joint development projects (JDPs) between manufacturers and classification societies are another important avenue for advancing hydrogen propulsion technology. These projects allow both parties to explore new technologies and develop tailored guidelines that ensure safety and performance. By participating in JDPs, manufacturers can gain a deeper understanding of the regulatory landscape and contribute to the development of standards that support the safe and efficient use of hydrogen propulsion in maritime applications.

Early involvement of classification societies in the design process is critical for ensuring that hydrogen-powered vessels meet evolving safety and regulatory standards. By engaging classification societies early in the design phase, manufacturers can align their vessel designs with the latest safety requirements and regulatory expectations. This early collaboration helps identify potential regulatory challenges and design modifications needed to meet classification requirements, reducing the risk of costly delays and redesigns later in the process. An early involvement of flag state is also recommended as soon as the application case is identified.

The Alternative Fuels Insight portal (afi.dnv.com) presents an up-to-date overview of the implementation of alternative fuel technology as well as an overview of the global orderbook and maps of relevant infrastructure. Using this information will help the stakeholders to build trust in the transformation of the maritime industry towards net-zero GHG emissions.

Policy Recommendations

- Direct public grants toward pre-competitive R&D on hybrid hydrogen-battery propulsion, with industry shouldering the cost of collaborative projects among shipyards, classification societies, and fuel-cell manufacturers.
- Consider cross-industry standards (e.g., SAE J2601 for fueling) to acceleratemaritime regulation development.
- For hydrogen powered vessels, liquid hydrogen would ideally become the most relevant fuel, therefore, liquid

hydrogen handling, storage, boil-off reduction and refueling processes & protocols need to be established. Collaboration with heavy-duty and aviation industry could help speed-up the development process due to similar synergies.

Infrastructure and Ecosystem Development

Infrastructure gaps present a major hurdle for hydrogen mobility in coastal areas. ITHCA stakeholders indicate that supply infrastructure developers face significant demand uncertainty, while potential adopters of hydrogen-powered vessels struggle with limited visibility into future supply chain developments. This creates a cycle of hesitation, where infrastructure investments are delayed due to uncertain demand, and vessel operators hesitate to transition due to unclear supply logistics.

A well-defined, ecosystem-wide strategy is necessary to break this cycle. Investment in hydrogen infrastructure should not be piecemeal but rather structured to encompass the entire value chain, from production and storage to distribution and end-user applications. Stakeholders highlight that best collaborations arise around concrete projects with defined resources, goals, and timelines.

In Europe, disparate national regulations and language barriers hinder collaboration. ITHCA stakeholders advocate for transnational frameworks and centralized port authority leadership to streamline compliance. Harmonized standards would provide a clear and consistent regulatory framework that supports the safe and efficient deployment of hydrogen propulsion in the maritime industry.

A regional or transnational regulatory framework would facilitate smoother operations, allowing manufacturers to standardize their products and streamline compliance processes. In addition, there is a need for more proactive coordination by authorities to balance hydrogen distribution and usage at ports. Unlike land-based hydrogen ecosystems, ports provide controlled environments where infrastructure planning could be more centralized.

Policy Recommendations

- Designate "Hydrogen Port Zones" in key maritime hubs (e.g., Rotterdam, Singapore) with centralized infrastructure for production, storage, and bunkering.
- Establish a €500 million EU Maritime Hydrogen Fund to co-finance port infrastructure and vessel retrofitting.
- Develop a transnational hydrogen supply chain task force to coordinate infrastructure planning across North Sea and Baltic states.
- Incentivize private investment through guaranteed offtake agreements for green hydrogen in maritime applications.

Policy Advocacy and Future Directions

Policy advocacy is another important aspect of advancing hydrogen propulsion technology. Classification societies often play a role in advocating for regulatory changes at the national and international levels. By working together, manufacturers and classification societies can ensure that their interests and innovations are represented in policy discussions, leading to more supportive regulatory environments for hydrogen technologies.

The general consensus is that risk perception should be managed through scientific evaluation and industry experience rather than excessive regulation. As stakeholders gain more knowledge and operational experience with hydrogen technology, regulators will likely amend initial rules and regualtions. ITHCA stakeholders emphasize that safety standards and regulations should be co-developed alongside industry players. Rather than viewing safety standards as external constraints imposed on the industry, there is a push for a more integrated development process where both regulation and safety measures evolve with technological advancements. This would ensure that regulatory frameworks remain relevant and adaptable rather than serving as obstacles to innovation.

Knowledge sharing and training are critical for advancing the adoption of hydrogen propulsion in the maritime industry. Collaboration between manufacturers and classification societies facilitates the exchange of knowledge and expertise, with classification societies providing insights into regulatory requirements and safety standards, and manufacturers offering technical details about new hydrogen technologies. This mutual learning accelerates the development of appropriate classification rules and supports the safe deployment of hydrogen-powered vessels.

Training programs offered by classification societies are another important resource for manufacturers, designers, and operators of hydrogen-powered vessels. These programs focus on the latest safety practices, regulatory updates, and handling of hydrogen systems, ensuring that all stakeholders are well-prepared to meet classification requirements. By investing in training and education, the maritime industry can build the technical expertise needed to support the widespread adoption of hydrogen propulsion.

Overly restrictive policies, driven by fear and lack of experience, slow down progress, while under-regulation poses potential safety risks. The key lies in striking a balance between precaution and innovation. Training and awareness efforts could play a significant role in overcoming current regulatory challenges. As industry professionals become more knowledgeable and experienced in handling hydrogen safely, regulatory bodies may feel more confident in providing practical and science-based safety measures. This would allow for the gradual but steady deployment of hydrogen-powered vessels without unnecessary bureaucratic slowdowns. The industry must advocate for regulations that are evidence-based rather than purely precautionary, allowing for the responsible and efficient adoption of hydrogen technology in maritime applications.

Policy Recommendations

- Establish a permanent Hydrogen Maritime Advisory Council under the IMO, with equal industry-regulator representation, to co-develop regulations.
- Considerhydrogen safety training for maritime stakeholders, incl regulators and insurers.

- Amend national maritime legislation to require any new vessel contracts, major refits or port infrastructure projects to include defined hydrogen-readiness criteria—tying R\&D tax credits and public-procurement advantages to demonstrable plans for PEM fuel-cell integration, modular H_2 storage scalability, and participation in a government-backed Monitoring, Reporting & Verification (MRV) program that unlocks accelerated permitting or additional innovation grants for operators exceeding efficiency and emissions-reduction benchmarks.

- Extend the scope of the EU's maritime Emissions Trading System to cover sub-5,000 GT craft operating within marine protected zones, requiring them to surrender allowances or pay equivalent environmental levies on fuels and docking. This measure would mandate emissions reporting, ensure small boats bear costs commensurate with their environmental impact, and direct auction or levy revenues into hydrogen-fuel R&D grants and tax credits—driving accountability and innovation in zero-emission propulsion.

- Establish designated emission control zones around urban coastlines and marine protected areas, requiring vessel operators to obtain emissions licenses and comply with stringent limits on NO_x, SO_x, PM and greenhouse gases. These zones would phase in near-zero-emission requirements—favoring hydrogen and other zero-emission technologies—through tiered permit fees and enforcement mechanisms.

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MONACO HYDROGEN ALLIANCE

www.monacoh2.org

info@monacoh2.org

Monaco Hydrogen Alliance
41 avenue Hector Otto
98000, MONACO