



(RESEARCH ARTICLE)



Fuelling the Future: Evaluating the perceived challenges to hydrogen fuel uptake in the superyacht sector

Harvey Merson-de Mendoza and Mehrdad Behforouzi *

Warsash Maritime School, Southampton Solent University, UK.

World Journal of Advanced Research and Reviews, 2025, 27(01), 2564-2597

Publication history: Received on 14 June 2025; revised on 26 July 2025; accepted on 28 July 2025

Article DOI: <https://doi.org/10.30574/wjarr.2025.27.1.2734>

Abstract

The superyacht industry, a symbol of luxury, significantly contributes to environmental degradation due to its reliance on fossil fuels, highlighting an urgent need for decarbonisation. Hydrogen Fuel Cell (HFC) technology presents a promising zero-emission alternative for maritime propulsion. This study examines professional perspectives on the barriers to HFC adoption in the superyacht sector, with a focus on technical feasibility, economic viability, and infrastructure readiness. Key challenges include large space requirements for fuel storage, integration complexities, high initial and operational costs, inadequate bunkering infrastructure, and the absence of comprehensive international regulations.

Using a mixed-methods approach, the research combines a literature review, a survey of 53 industry professionals, and interviews with three experts. Findings reveal that low volumetric energy density of hydrogen and a regulatory deadlock, where supply and policy are mutually dependent, impede progress. Safety concerns and a lack of public awareness further discourage adoption.

Despite these challenges, HFC technology holds potential to decarbonise superyachts. The study recommends forming a cross-industry hydrogen task force, increasing investment in RandD for fuel storage and hybrid systems, and developing standardised crew training. Collaborative efforts across the industry are essential to unlocking hydrogen's potential and fostering a sustainable future for luxury maritime transport.

Keywords: Superyacht; Decarbonisation; Future fuels; Hydrogen fuel; Competency

1. Introduction

Superyachts, symbols of luxury and opulence, travel around the world with extensive amenities, serving the ultra-wealthy. It comes at a cost, as massive consumption of hydrocarbon fuels produces vast amounts of Carbon Dioxide (CO₂), causing this industry to go under the spotlight, creating controversy and highlighting the need for greener, decarbonising options.

Proton Exchange Membrane (PEM) fuel cells, with hydrogen fuel, provide a decarbonising solution by transforming hydrogen and oxygen into electrical energy while producing water and heat as its only byproducts. The zero-emission hydrogen propulsion option meets worldwide sustainable energy expectations, which positions hydrogen as an ideal fuel for superyachts [1].

The study investigates industry professionals' perspectives to identify obstacles preventing hydrogen fuel technology implementation. The dissertation utilises a mixed-methods approach, with a literature review that includes case studies

* Corresponding author: Capt. Mehrdad Behforouzi/ ORCID: 0000-0001-9753-871X

to address regulatory pressures, such as the International Maritime Organisation's (IMO) emission targets and sustainable yachting interests, by identifying barriers and suggesting adoption strategies.

1.1. Background

The superyacht industry accounts for a considerable portion of global Greenhouse Gas (GHG) emissions, which have steadily increased over the last ten years. Our unyielding dependence on traditional fossil fuels leads to environmental issues which demand urgent and comprehensive intervention [2].

In 2023, the IMO implemented a change to address this growing emergency. Their revised strategy (2023 IMO GHG Strategy) sets an uncompromising target to tackle this exponential problem. The IMO plans to reach net-zero GHG emissions in international shipping operations by 2050. An ambitious objective exists alongside essential short-term targets and regional enforcement of strict emission rules, ensuring a necessary movement toward preventing environmental damage [3,4].

In the urgent search for solutions to environmental challenges, hydrogen fuel cells present an optimistic solution. These systems deliver an uncompromisingly clean energy solution which results in no harmful emissions. Although current hydrogen production methods remain dependent on fossil fuels, hydrogen's superior zero-emission capability establishes it as a necessary option for achieving sustainable maritime operations [5].

1.2. Research problem

Fuel cells are devices that utilise electrochemical processes to transform the chemical energy of hydrogen and oxygen into electricity, heat, and water. Utilising hydrogen fuel cells in maritime applications could significantly decrease GHG emissions and enhance energy efficiency [6].

The potential of HFC technology for superyacht decarbonisation is recognised, yet its widespread use continues to be restricted as most ongoing projects are still relying on conventional fuels. Few pioneering superyacht projects have reached completion, which reveals a substantial divide between theoretical potential and real-world execution [7].

Research lacks detailed information about the specific obstacles and their impact that prevent hydrogen from being widely adopted for superyachts.

Research literature recognises hydrogen's limitations, such as low volumetric energy density, storage difficulties, safety risks and expensive implementation. Yet this lacks detailed analyses quantifying these effects for superyacht design and operation [8].

Current study compares hydrogen systems with stationary applications but does not supply a defined framework for maritime use while ignoring how marine atmosphere corrosion affects hydrogen systems [9].

However, extensive studies on the challenges posed by inadequate bunkering infrastructure and ambiguous international regulations, which obstruct the adoption of superyachts, remains insufficient [10].

Research efforts must target this gap because hydrogen offers substantial benefits to reducing superyacht carbon emissions and supporting the IMO's net-zero GHG emissions goals by 2050. Utilizing this technology would contribute to resolving wider problems specified in International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI through substantial reductions in emissions of harmful pollutants.

The study seeks to address a significant gap by empirically examining the real-world barriers that obstruct hydrogen fuel adoption in the superyacht industry to support better decision-making and strategic planning.

Aims and Objectives

The primary aim of this study is to identify and assess the perceived obstacles affecting the superyacht industry's adoption of HFC technology. The study includes assessing professional opinions about the technical feasibility, economic viability, readiness of infrastructure and compliance with relevant regulations.

The study will achieve this fundamental aim by executing several targeted objectives

- To ascertain how well superyacht industry professionals understand HFC technology, their primary concerns are its technical feasibility, challenges of safety, storage, and integration.
- To assess industry opinions about hydrogen refuelling facilities and essential development needs that support hydrogen technology adoption on superyachts while evaluating how these aspects function as obstacles.
- To investigate opinions on regulatory frameworks, classification society guidelines, and industry partnerships regarding hydrogen-powered superyachts to uncover perceived shortcomings and improvement requirements.
- To evaluate the perceived economic feasibility of HFC systems for superyachts by comparing them with traditional fuels and other alternative power options and analysing government incentive impacts.
- To explore the influence of owner and guest perceptions of hydrogen safety on the superyacht sector and to determine actionable solutions to alleviate associated concerns.
- The study will systematically follow these objectives to achieve a thorough knowledge of HFC technology adoption challenges and opportunities inside the superyacht industry.

1.3. Significance of the study

There are challenges regarding the use of HFC. For example, the difficulties of storing hydrogen in gaseous and liquid states, along with the necessary procedures for its handling, transportation, and storage, clarify the comprehensive needs for hydrogen storage based on its volumetric density. Due to its innovative approach to shipping, few studies have examined the elements that affect the decision to implement HFC. Although earlier studies have pinpointed the factors that encourage and hinder the adoption of zero-emission technologies, there is a shortage of an extensive analysis from an organisational viewpoint that focuses specifically on HFC [11].

This study targets the pressing requirement for sustainable maritime solutions, specifically within the superyacht industry.

Firstly, it will evaluate perceived barriers to hydrogen adoption to deliver an essential understanding of marine decarbonisation, which supports the development of eco-friendly technology for superyachts.

Secondly, stakeholders, such as ship managers, engineers, researchers, technicians and shipyard representatives, will gain valuable perspectives from findings that assess hydrogen's technical/economic feasibility and market readiness. This informs design, investment, and operational strategies.

Thirdly, this analysis responds to rising global regulatory pressures, such as the 2023 IMO GHG strategy, by revealing hydrogen adoption barriers, which helps policymakers and classification societies create better regulations and incentives for clean fuels.

Finally, the mixed-methods approach, which combines quantitative surveys with qualitative interviews, creates a comprehensive understanding through the identification of broad trends and rich contextual details. The combined methodology approach improves validity through actionable insights that drive hydrogen adoption and promote sustainable superyacht operations.

1.4. The problem with existing fossil fuels

The 2023 study by Krantz *et al.* offers an extensive life-cycle evaluation of different marine fuels and detailed figures of CO₂ emissions from combustion. The paper details the amount of CO₂ emissions in grams for every Megajoule of propulsion energy produced [12].

Based on that, the author calculated the amount of CO₂ produced for each tonne of fuel by multiplying the combustion emissions by energy per Kg of fuel (CO₂/MJ propulsion X a MJ fuel/Kg fuel) before standardising the unit and dividing this by the energy value of the fuel per Megajoule of propulsion. Finally, it was converted back to tonnes by multiplying this number by one thousand.

Table 1 Amount of CO₂, in tonnes, produced after the combustion of four different conventional marine fuels

<p>High-Sulphur Fuel Oil (HSFO):</p> $\frac{(150g \text{ CO}_2/\text{MJ Propulsion} \times 40\text{MJ fuel/Kg fuel} \times \frac{1\text{Kg}}{1000g})}{2.01 \text{ MJ fuel/MJ Propulsion}} \times 1000 = 3.022 \text{ t CO}_2/\text{t fuel}$
<p>Very-Low-Sulphur Fuel Oil (VLSFO):</p> $\frac{(150g \text{ CO}_2/\text{MJ Propulsion} \times 43.1\text{MJ fuel/Kg fuel} \times \frac{1\text{Kg}}{1000g})}{2.01 \text{ MJ fuel/MJ Propulsion}} \times 1000 = 3.216 \text{ t CO}_2/\text{t fuel}$
<p>Marine Gas Oil (MGO):</p> $\frac{(146g \text{ CO}_2/\text{MJ Propulsion} \times 43.1\text{MJ fuel/Kg fuel} \times \frac{1\text{Kg}}{1000g})}{2.04 \text{ MJ fuel/MJ Propulsion}} \times 1000 = 3.085 \text{ t CO}_2/\text{t fuel}$
<p>Liquefied Natural Gas (LNG):</p> $\frac{(114g \text{ CO}_2/\text{MJ Propulsion} \times 39\text{MJ fuel/Kg fuel} \times \frac{1\text{Kg}}{1000g})}{1.96 \text{ MJ fuel/MJ Propulsion}} \times 1000 = 2.268 \text{ t CO}_2/\text{t fuel}$

Source: Mendoza

1.5. Existing Government Targets

The work by Anantharaman, Sardar and Islam (2025) provides essential data about the IMO’s objectives. The paper details the IMO's step-by-step approach to cutting emissions, referencing 2008 as the starting point. International shipping must achieve a 40% reduction in carbon intensity by 2030 while minimising total GHG emissions by 20% (with a 30% target) and implementing zero or near-zero emissions fuels or technologies to cover 5% of shipping energy needs (aiming for 10%). The checkpoint target for 2040 sets a minimum 70% reduction in total annual GHG emissions to reach an 80% reduction. The interim steps contribute to fulfilling the long-term goals of the sector. The revised 2023 IMO strategy aims for international shipping to achieve net-zero GHG emissions by the year 2050 or shortly thereafter [13].

According to the UK Department for Transport (2025), the UK government has embarked on implementing the IMO 2023 strategy by applying the domestic Maritime Decarbonisation Strategy (MDS). The published UK maritime strategy sets a timeline for “Net-Zero” and “Well-to-Wake” GHG emissions in domestic shipping by 2050 [14]. A structured timetable has been developed for this strategy

Table 2 Domestic maritime decarbonisation strategy timeline

Year/Period	Category	Event/Milestone
pre-2025	International Policy	IMO GHG negotiations (continuous)
	Domestic Policy	International Green Corridor Fund and Clean Maritime Demonstration Fund run until March 2025
		Clean Maritime Demonstration Competition (CMDC) round 6 launches
		Technical consultation on expanding the UK Emission trading scheme (ETS) to domestic maritime
		Call for evidence on: Net Zero Ports; Measure for small vessels and emissions uptake in targeted subsectors
		Primary legislation required for: UK fuel regulations; Zero Emissions Berth requirement; Measures for small vessels and emissions uptake in targeted subsectors; IMO mid-term measures
2025		IMO Approval and Adoption of mid-term GHG reduction measures

	International Policy	Fuel EU Maritime regulation (FuelEU) implementation
2026	Domestic Policy	UK ETS comes into force, proposed for vessels over 5000GT
		Consultation on at berth measure
		Consultation on measures for targeted subsectors
		Initial evaluation report of UK SHORE 1.0
		First formal consultation on UK fuel regulations
2027	Domestic Policy	MDS Review
		Earliest point from which measures aimed at smaller vessels could be introduced
2028	International Policy	IMO GHG 2028 Strategy revision
	Domestic Policy	Proposed UK ETS threshold review
		Zero Emission Vessels and Infrastructure (ZEVI) projects complete self-funded 3-year demonstration
2030	International Policy	IMO 20-30% International Target (Reduction)
	Domestic Policy	30% Interim Goal (Reduction)
2030-2040	International Policy	Anticipated IMO GHG 2028 Strategy revision
		Anticipated IMO revision of midterm measures
	Domestic Policy	UK fuel regulations introduced
		Potential measures for at berth emissions introduced
		Proportionate measures aimed at smaller vessels introduced where appropriate
2040	International Policy	IMO 70-80% International Target (Reduction)
	Domestic Policy	80% Interim Goal (Reduction)
2040-2050	International Policy	Some global measures increase in stringency
	Domestic Policy	Some UK measures increase in stringency
2050	International Policy	Earliest date from which IMO long-term GHG reduction measures could come into force
	Domestic Policy	Zero Emission Maritime
		Clean Maritime Hub (Drives)

Source: UK Department for Transport 2025

1.6. Superyacht Market and Current Projects

Allied Market Research (2023) quantifies data showing that the global Superyacht market was valued at \$10.3 billion (£8.2 billion) in 2022. They also predict that by 2032, this will have grown significantly to \$25.7 billion (£20.5 billion), representing a compound annual growth rate of 9.8%. Market research shows a significant growth in Yachts above 80 metres in size by 2032 compared to the initial findings taken in 2022. This data also highlights that countries such as Italy, Spain, Germany, and the United Kingdom are witnessing an increase in the popularity of “sustainable and eco-friendly” yachts, which aligns with this region’s strong emphasis on environmental conservation [15].

The Superyacht Report by TRP Magazines (2025) examines hydrogen deployment, market share analysis, and environmental effects in the superyacht market [16].

- The superyacht order book totalled €25.3bn in 2022, representing a substantial segment of the €33bn global yachting market. Regarding unit numbers, superyachts occupy 1% of the luxury market, while vessels between 24-40m Length Over All (LOA) make up 80% of the superyacht fleet.
- The maritime industry generates substantial environmental damage due to its dependency on fossil engines, which emit CO₂, Nitrogen oxides (NO_x), and particulate matter. The industry is also struggling to meet IMO Tier III standards.
- Feadship's Project 821, named "Breakthrough", represents a new development in hydrogen fuel technology. It is the world's first superyacht powered by green hydrogen fuel cells, providing zero-emission "hotel load" and enabling "short-range cruising". Gulf Craft is also researching Liquid Organic Hydrogen Carrier (LOHC) systems.

MAN, Energy Solutions (2024) supplied and installed the hydrogen system onboard "Project 821". In a press release, the company highlighted many challenges with the design, installation and operation of the system. MAN faced substantial project difficulties because there were no established design codes or standards for liquid hydrogen tanks to obtain approval. The International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF) code is the standard for designing Type C LNG tanks but does not fully cover hydrogen applications. MAN, and Lloyd's Register (a leading classification society) jointly established a risk assessment-based design process to secure safety approval for below-deck liquid hydrogen tank installation. The alternative method for design approval faced difficulties, which demonstrated the trailblazing efforts needed and the bureaucratic obstacles present in creating sustainable marine fuel solutions [17].

1.7. Environmental effects of yachts

The report by Lloret and Carreno (2020) examines the environmental consequences of yacht engine usage within Marine Protected Areas (MPA). The Mediterranean MPAs face substantial ecosystem pressure from the operation of engines onboard large yachts (>24m), which congregate in these sensitive areas. Pollutants such as fuel, oil, heavy metals, and Polycyclic Aromatic Hydrocarbons (PAH) emitted from engines enter water sources through exhaust gases and bilge water, resulting in water pollution and bioaccumulation. Exhaust emissions produce air pollution, which leads to environmental deterioration [18].

1.8. Existing Methods of Decarbonisation

The study by Tay and Konovessis (2023) evaluates existing sustainable propulsion systems for maritime transport while exposing various adoption barriers specific to sea transport settings. Renewable energy sources face significant challenges in maritime operations because weather-dependent wind and solar resources display unpredictable patterns which undermine system reliability. The authors state that alternative fuels, such as LNG, hydrogen, and ammonia, require special handling procedures and present safety risks, including flammability and toxicity. The requirement for ships to have high-energy-density power systems introduces engineering challenges to the integration of sustainable technologies, as renewable options, such as wind and solar, face physical limitations (height and deck space) that prevent the provision of complete power for large ships. The demand for alternative fuels has increased storage capacity requirements (LNG, hydrogen, ammonia), which in turn affects ship design and stability [19].

A study by Karatug, Arslanoglu, and Guedes Soares (2022) presents an assessment of decarbonisation methods for current ships [20]. The study describes multiple operational methods already in practice:

- Wind energy harnessing methods use Flettner rotors, kites, wind turbines, and wing sails. Although a ship can sail faster than the wind and still power Flettner rotors to generate energy, the direction of the wind remains an essential factor. Research indicates that Flettner rotors provide up to a 20% reduction in fuel consumption, as demonstrated by the "E-Ship1" project.
- Slow steaming is the concept of lowering a ship's speed, which reduces fuel consumption and emissions by enhancing energy efficiency throughout its operational processes.
- Engine derating optimises ship engines to operate at lower speeds continuously, which lowers fuel consumption by 10-12%.
- Waste heat recovery systems generate electricity by capturing waste heat from thermal processes, such as exhaust gas emissions, without requiring extra fuel.
- Carbon Capture and Storage systems (CCS) extract CO₂ from the exhaust gas, achieving reduction levels between 85% and 90%.

- Air Lubrication Systems (ALS) utilise an air layer between the ship's hull and seawater to reduce frictional resistance, resulting in a 7.5% to 15% increase in energy efficiency while reducing emissions.

The authors Wang, Zhang, and Zhu (2023) state that nuclear energy serves as a decarbonisation solution for marine fuel but faces substantial obstacles. The primary advantage of nuclear propulsion systems is their ability to prevent operational emissions of greenhouse gases, such as CO₂, NO_x, and Sox, which supports the shipping industry's transition towards environmentally friendly practices. Nuclear power enables ships to operate for extended periods without refuelling, providing increased autonomous capabilities.

Despite these advantages, significant obstacles remain. The development of nuclear merchant ships has faced challenges due to their high operational costs, regulatory hurdles and limited port acceptance. The hazardous nuclear events, such as Chernobyl, have created negative public sentiments, resulting in social and political obstacles against adoption. The outdated and disjointed international regulatory framework poses the most significant challenge, as it has lagged technological advancements. The absence of precise crew training requirements and effective liability systems, coupled with fragmented safety and port access rules, makes commercial deployment of nuclear ships currently impractical [21].

- A study by Gil *et al.* in 2013 examined the financial feasibility of nuclear propulsion for ships, identifying multiple cost-related variables [22].
- A nuclear ship's initial Capital Expenditure (CAPEX) significantly exceeds that of diesel ships due to the main engine costing \$270 million. In comparison, diesel ship engines cost \$18 million, and nuclear vessels include an additional 10% contingency fee.
- The Operation Expenditure (OPEX) for a nuclear ship saves \$36 million annually, although expenses such as fuel cycle management, fuel exchange, waste disposal, crew costs and insurance persist.
- The cost of nuclear reactors plays a crucial role in the economic feasibility of nuclear propulsion, which remains viable when reactor costs stay under \$ 4,000/kW.
- The economic evaluation of operations is affected when changes in oil prices influence CAPEX and OPEX.

The maritime sector faces significant challenges in adopting nuclear propulsion due to financial constraints combined with the high costs of reactors and fuel.

1.9. Hydrogen Fuel Cells

- The study by Wang *et al.* (2024) examines fuel cell technology for ship power and reveals multiple challenges and obstacles hindering its adoption within the maritime environment:
- The maritime operational environment presents significant challenges, including harsh saltwater corrosion, while demanding high durability and energy density solutions for long voyages due to limited refuelling opportunities.
- Ships require power systems that surpass land-based system requirements in both robustness and energy capacity, creating substantial engineering obstacles for fuel cell systems.
- The production and transportation of hydrogen fuel present complex supply chain challenges which require the development of environmentally sustainable hydrogen supply networks.
- The adoption of fuel cell technology in the maritime industry is at an early stage compared to other sectors, meaning that more research and development are required to optimise systems and improve efficiency while addressing specific limitations such as the reduced lifespan of some types of fuel cells, for instance, Low-Temperature Proton Exchange Membrane Fuel Cells (L-T PEM FC).
- An examination of the economic feasibility of fuel cell systems for ships' power highlights significant challenges due to the high starting costs of different fuel cell types, which are designed to survive the vessel's long operational life. It increases the necessity for additional cost-reduction techniques [23].

A 2022 analysis by Pourrahmani *et al.* examines PEM fuel cells as viable, low-pollution alternatives to combustion engines. The main benefits are zero direct emissions, as they only produce water as a byproduct, along with performance capabilities that match conventional vehicles in terms of range and refuelling time. Lower operating temperatures, ranging from 65-85°C, are a key advantage compared to other fuel cell systems. However, significant challenges hinder widespread adoption. A major barrier remains high expenses, primarily driven using platinum catalysts. Two fundamental operational problems are managing complex water systems required for maintaining proper hydration while preventing flooding and maintaining system performance through precise thermal management within a limited operational temperature range. Improvements are needed to address issues of durability, reliability, and cold-start capabilities. The commercialisation of fuel cells faces major obstacles due to catalyst degradation and

poisoning (reduced electrode activity caused by contaminated Fuel or air), as well as system complexity and insufficient hydrogen infrastructure [24].

1.9.1. Hydrogen Fuel Storage Technology

The study conducted by Berkehan Inal, Dere and Deniz (2021) analyses various hydrogen storage technologies for maritime applications and identifies numerous implementation barriers:

- The limited "volumetric energy density" of hydrogen gas requires complex storage systems that may occupy a large amount of space for marine vessels, which presents significant design challenges.
- The high costs and safety risks associated with high-pressure tanks storing compressed hydrogen coexist alongside the extreme cryogenic temperatures and boil-off problems encountered in liquid hydrogen storage. In contrast, solid-state and liquid carrier methods require complex thermal management and the use of catalysts.
- The maritime sector faces significant logistical and supply chain challenges in building global bunkering infrastructure, ensuring secure hydrogen supplies, and developing safe operational procedures.
- Shipboard hydrogen systems lack full technological maturity. Managing hydrogen flammability risks and carrier toxicity issues, such as ammonia leaks, remains crucial for safe operations.

Technical limitations, infrastructural shortcomings, and safety concerns pose significant barriers to implementing hydrogen storage systems on board ships. According to the authors, widespread adoption cannot be achieved without substantial development [25].

1.9.2. Cost of HFC Technology

The 2017 study by Grahn, Brynolf, and Taljegård presents the production costs for liquid hydrogen, resulting in a base cost of €116/MWh. Investment costs for Fuel Cell (FC) propulsion and storage are substantial, depending on vessel type. Coastal vessels require an investment of approximately €23.77 million per vessel. In comparison, deep-sea vessels need an investment of approximately €118.31 million per vessel, and container vessels demand an investment of approximately €201.95 million per vessel for FC propulsion and storage systems. The study shows that hydrogen fuel costs less than electro fuels. However, FC system installation costs exceed those of Internal combustion engines (ICE). The replacement costs for fuel cell stacks, which range from €0.26 million to €2.87 million depending on vessel type, contribute to operational expenses yet are regarded as minimal on the overall cost scale. Hydrogen FCs demonstrate cost advantages over electro-diesel and ICEs on vessels that operate for more than 150 days per year, according to the base scenario analysis; however, this changes when lower fuel production costs are considered [26].

1.9.3. Benefits of HFCs

Sürer and Arat (2022) analysed HFC technology for marine vehicles by examining their benefits and potential future developments

- **Advantages:** Hydrogen fuel cells deliver greater efficiency with near-zero emissions during operation while producing less noise and requiring less maintenance than diesel engines. They also provide improved performance under partial load conditions.
- **Future Advancements of Green Hydrogen:** The focus involves lowering the costs associated with green hydrogen production through electrolysis and resolving infrastructure challenges.
- **Future Advancements in Onboard Production:** The innovative onboard hydrogen production method, utilising seawater electrolysis (either directly or after desalination), requires further development to address corrosion-related challenges.
- **Future Advancements of Storage and Fuel Cell Technology:** To make progress, advances in hydrogen storage density, together with increased fuel cell durability through methods such as non-precious metal catalysts, are essential [27].

1.9.4. Hydrogen Production

Ishaq, Dincer and Crawford (2021) highlight the global shift to renewable energy as essential. While hydrogen serves as a critical element in energy transition efforts, its traditional 'grey' production method, which relies on fossil fuels, generates significant CO₂ emissions. The researchers emphasise the critical need for 'green hydrogen' production, which utilises electrolysis powered by renewable energy sources, such as solar and wind energy [28].

- Environmental decarbonisation, alongside the practical use of renewable energy, demands the use of green hydrogen.
- Blue hydrogen production from fossil fuels involves CCS, although concerns exist about its efficiency and the long-term safety of storage [29].
- Nuclear energy is used to produce purple hydrogen, which ensures there are no direct emissions during its generation.

The review concludes that green hydrogen represents the legitimate, sustainable, and carbon-free solution needed to achieve worldwide decarbonisation targets.

1.9.5. Training and competency

The 2024 report from the Maritime Just Transition Task Force (MJTTF) is a crucial document that reveals substantial obstacles and essential training requirements for seafarers who use hydrogen as a marine fuel. Industry professionals recognise hydrogen as potentially the most complex new fuel due to its limited operational history and distinctive properties. These differ from both traditional fuels and other alternative fuels, such as ammonia and methanol [30,31].

The primary challenges of using hydrogen fuel stem from its high flammability, which necessitates the development of new flame detection systems and enhanced fire safety protocols. The industry is acutely aware of these risks and is proactively developing solutions to ensure safety.

- A comprehensive transformation in training and competencies for seafarers is expected across vital domains, including:
- A deep comprehension of the unique physical, chemical and hazardous characteristics of CH₂ and LH₂.
- Process safety, including fuel handling, bunkering management, storage, operational knowledge of cryogenic fuel systems, and fuel preparation.
- Correct usage of hydrogen leak and flame detection devices, including calibration.
- Hydrogen fire risks, correct firefighting methods, ventilation requirements and Emergency Shutdown (ESD) procedures.

The MJTTF recommends that these comprehensive revisions be incorporated into seafarer training programs, which are crucial for the safe use of hydrogen in the maritime sector. Failure to update these programs could lead to increased safety risks, potential accidents, and environmental damage.

2. Materials and Methods

The study uses multiple methods to assess the perceived barriers to adopting HFC technology within the superyacht industry. The study methodology combines quantitative data collection methods, such as surveys, with qualitative data collection techniques, including semi-structured interviews. The dual approach provides a comprehensive overview of industry viewpoints, allowing for a detailed examination of specific topics.

2.1.1. Research Design

The study aims to systematically collect and analyse information from various stakeholders in the superyacht industry. The survey phase of the quantitative research investigates overall trends and widespread perceptions, as well as the presence of specific challenges. The qualitative phase, through interviews, provides enhanced contextual details and deeper insights into the subtle complexities of stakeholder perceptions and challenges. A comprehensive understanding of the research problem is reliant on the combined power of these dual methods.

2.2. Data Collection Methods

2.2.1. Surveys (Quantitative Data Collection)

The primary approach to collecting quantitative data will be via online surveys.

- Purpose: The survey gathers information from various industry professionals regarding their perspectives and experiences, as well as their concerns related to HFC systems. The investigation will examine technical feasibility components, including safety and storage, as well as economic viability through operational costs and maintenance expenses. It will also evaluate regulatory barriers and adoption opportunities for hydrogen technology in superyachts.

- **Survey Instrument:** The questionnaire comprises approximately fifteen multiple-choice questions that solicit targeted responses from participants regarding essential research topics. The questions examine participants' knowledge of hydrogen technology, including technical obstacles and infrastructure impediments, lifecycle expenses, regulatory issues, and influential adoption factors.
- **Target Audience:** This study's survey aims to reach approximately fifty to sixty stakeholders who are part of the superyacht industry. The group comprises yacht managers, Captains, chief engineers, engineering officers, technicians, naval architects, owner representatives, and researchers. The selected group provides multiple viewpoints from participants who hold various positions and have diverse experiences in the field.
- **Distribution:** The survey will be distributed using the JISC online survey platform, which Solent University provides. Professional networks, such as LinkedIn and industry contacts, will be utilised to identify and engage potential participants.
- **Data Analysis (Quantitative):** Descriptive statistics (including frequencies, percentages and means) will process survey data to produce response summaries and detect widespread patterns. When necessary, the researcher will employ inferential statistics to investigate relationships between variables, such as the correlation between experience levels and perceptions of technical feasibility. The findings will be presented through graphs and charts for clear and concise representation.

2.2.2. *Semi-structured Interviews (Qualitative Data Collection)*

Through semi-structured interviews, researchers will gather enhanced and nuanced insights.

- **Purpose:** The interviews will explore the practical application of HFC technology, as well as its effects on vessel operations and potential industry-wide adoption. The study will investigate maintenance challenges alongside specialised tools and training requirements and expected lifecycle costs.
- **Interview Instrument:** The semi-structured interview approach uses a framework of ten open-ended questions to guide the discussion. The flexible format supports the investigation of new themes and permits participants to explain their experiences and viewpoints. The guiding questions will cover areas such as technical challenges, economic feasibility, transition approaches, partnership initiatives, policy structures, Research and Development (RandD) activities, power system controls, infrastructure impacts, design plans, and perceptions of owner and guest safety.
- **Target Audience:** The study will conduct interviews with three industry experts with varying levels of experience with hydrogen systems. The selected participants for this group will comprise of:
 - A shipyard representative from the company that recently built a hydrogen-fueled vessel will interview the interviewee, who will expand on the challenges faced by the company when constructing this large superyacht.
 - Researchers who possess theoretical expertise of hydrogen systems, their current applications, as well as their sustainability and their future potential.
- **Procedure and Recording:** Interviews will be conducted either via Microsoft Teams or in person, depending on the participant's availability and preferences. Participants who provide explicit consent through the informed consent form will allow interviews to be recorded using Microsoft Teams' recording tool and/or digital voice recorders to guarantee accurate data capture.
- **Data Analysis (Qualitative):** Interview recordings will be transcribed. The researcher will conduct a thematic analysis of the transcribed data. The analysis process involves becoming acquainted with the data, identifying and reviewing potential themes, and defining and naming them, resulting in the generation of a report. The study will incorporate direct quotations (with permission and anonymised data) to demonstrate essential results.

2.3. **Methodological Synergy**

The study approach integrates surveys with semi-structured interviews to produce methodological synergy. The quantitative survey data will provide comprehensive insights into perceptions and reveal prevalent industry problems. Qualitative interview data will provide a deeper contextual understanding of issues by examining underlying reasons for specific viewpoints and uncovering complexities in both challenges and opportunities. The study findings will achieve greater validity and reliability through data triangulation.

2.4. **Ethical Considerations**

Ethical conduct is paramount throughout this study. The Solent University Ethics Committee approved this study on 2 April 2025, under Reference Number 002084. This study will follow these ethical procedures without exception.

2.5. Limitations of the Methodology

The methodology of this study includes several identified potential limitations.

- **Sample Size and Generalizability:** The study aims to engage with a diverse group of survey respondents and interviewees; however, the results may not apply to the entire superyacht industry due to the selected sample. The specialised use of hydrogen in this field reduces the number of industry personnel who have firsthand experience.
- **Access to Participants:** The limited availability of industry professionals for surveys and in-depth interviews may impact data quality.
- **Self-Report Bias:** Data from surveys and interviews depends on participant-reported perceptions and experiences, which could be affected by recall bias or social desirability bias.
- **Rapidly Evolving Technology:** Both HFC technology and its corresponding regulations remain in a state of constant evolution. The collected data represents a momentary view, which may be inaccurate in the future.
- **Confidentiality Concerns:** Various potential participants and organisations may be reluctant to provide detailed information due to commercial sensitivities or confidentiality agreements that protect specific projects or technologies.

Although the mixed-methods approach faces certain limitations, it aims to deliver a valuable and solid understanding of the perceived challenges to hydrogen fuel adoption in the superyacht market.

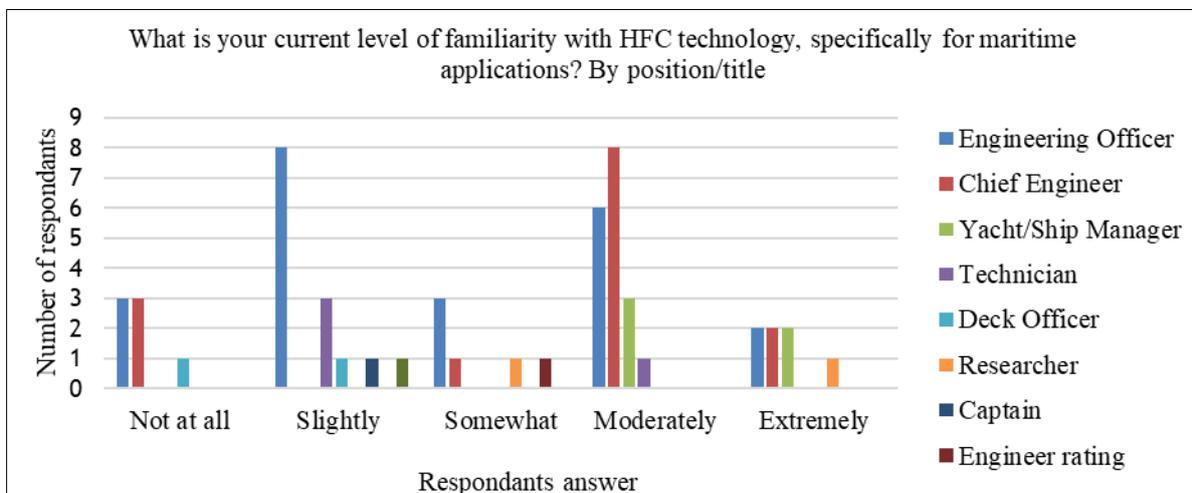
3. Results

3.1. Survey Results

The survey gathered input from fifty-three industry professionals. The data from respondents who failed to answer a question has been excluded from the specific analysis. Therefore, the number of responses included in each analysis graph or chart may vary and does not necessarily match the total number of survey participants.

To achieve a precise analysis and a comprehensive understanding of trends, where relevant, two separate graphs were created through cross-referencing of survey data. The survey approach enables assessments based on the respondent's professional standing in the maritime industry, as well as their familiarity with hydrogen systems, as reported by the respondent. The dual analysis delivers enhanced context by showing the combined effects of professional experience and technical knowledge on perceptions of challenges.

3.1.1. Familiarity by Position



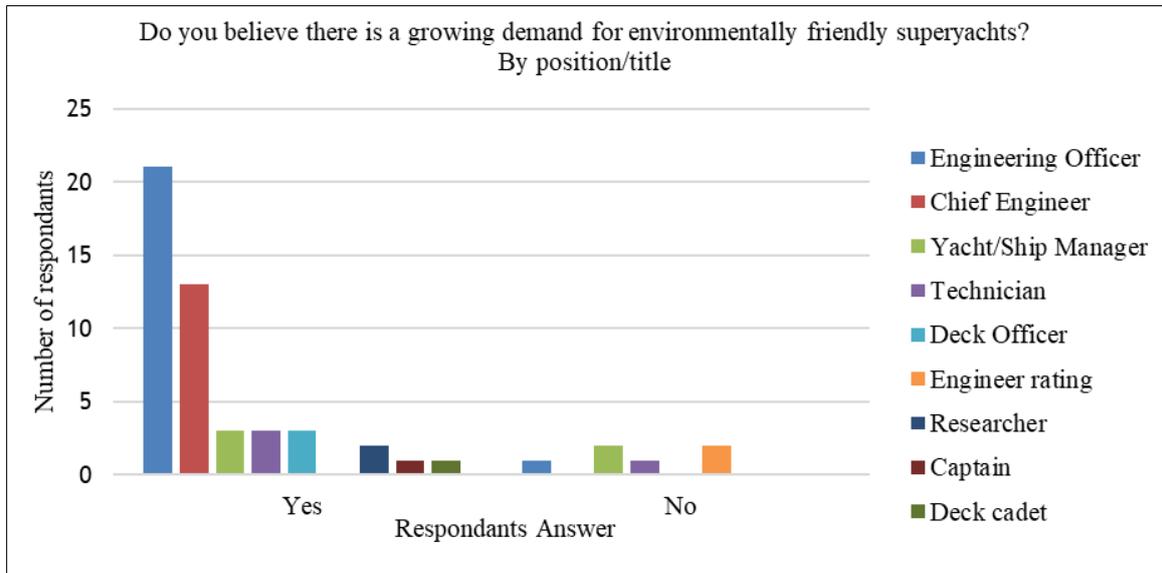
Source: Mendoza

Figure 1 Current level of familiarity with HFC technology

Figure 1 reveals distinct differences in knowledge of HFC technology across various maritime roles. Engineering officers and chief engineers, who hold technical and managerial positions, typically demonstrate moderate to high familiarity,

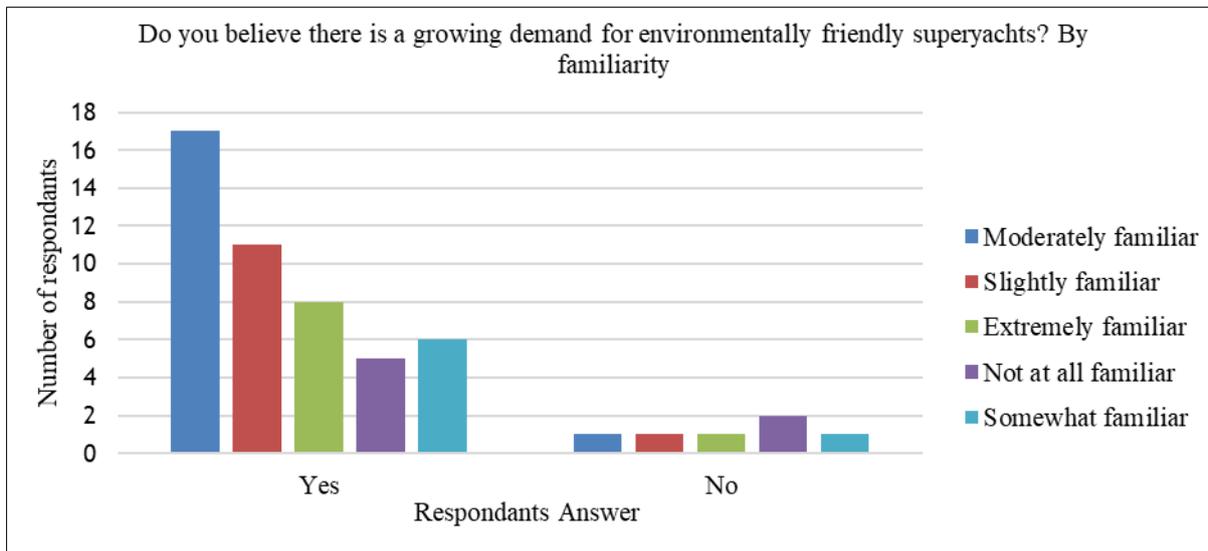
with many ratings themselves as “moderately” familiar. In contrast, deck officers, technicians, and deck cadets, primarily in operational or entry-level roles, report being only “slightly” familiar or “not at all” familiar with the technology.

3.1.2. Perceived demand for environmentally friendly yachts



Source: Mendoza

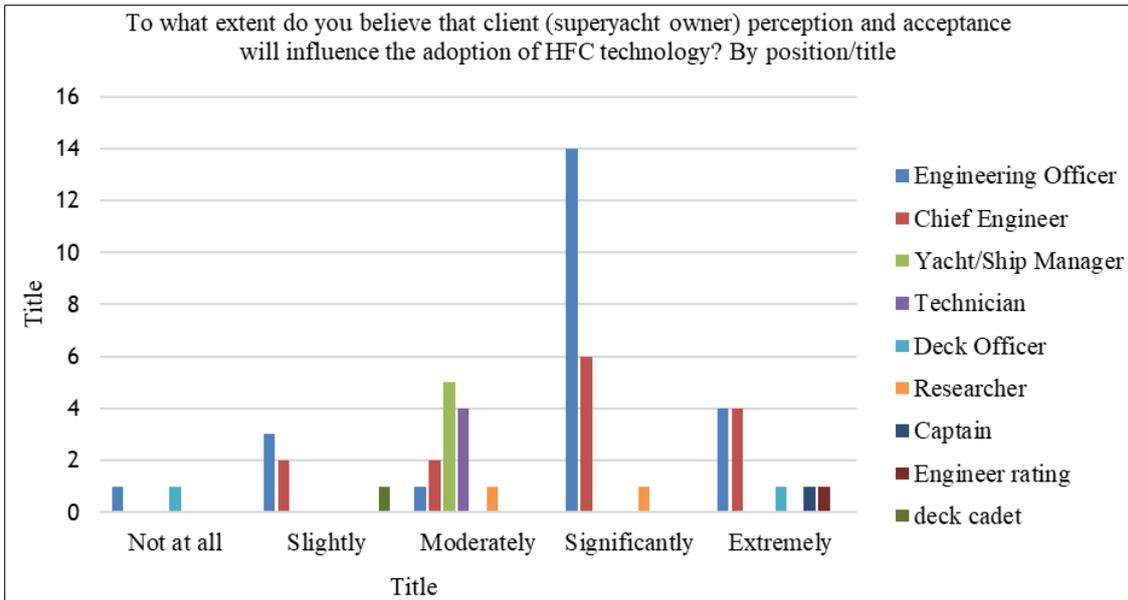
Figure 2 Demand for environmentally friendly superyachts



Source: Mendoza

Figure 3 Demand for environmentally friendly superyachts, by familiarity

Figures 2 and 3 highlight a widespread perception of demand for environmentally friendly superyachts among participants with varying levels of familiarity (Figure 3) and across different job roles (Figure 2). The largest group of participants expressed a growing demand for hydrogen technology, demonstrating strong agreement across all levels of familiarity with the technology. Most positions, including engineering officers and chief engineers, recognise this demand, while engineer ratings and yacht/ship managers demonstrate a comparatively stronger disagreement.

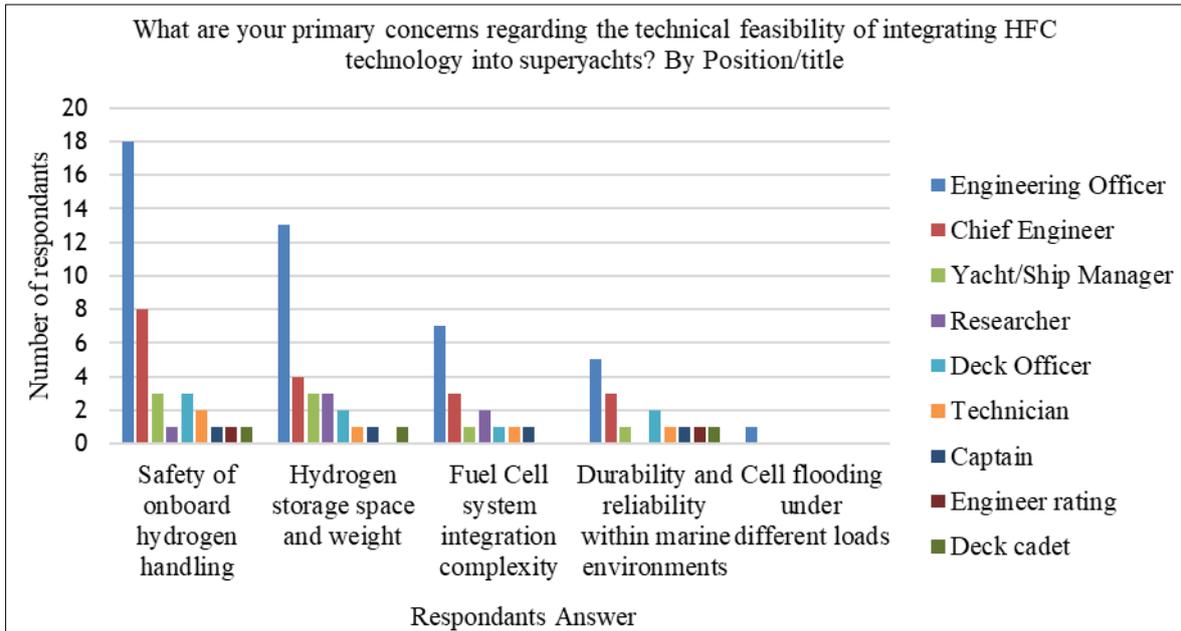


Source: Mendoza

Figure 4 Perception of client influence on the adoption of HFC technology, by position/title

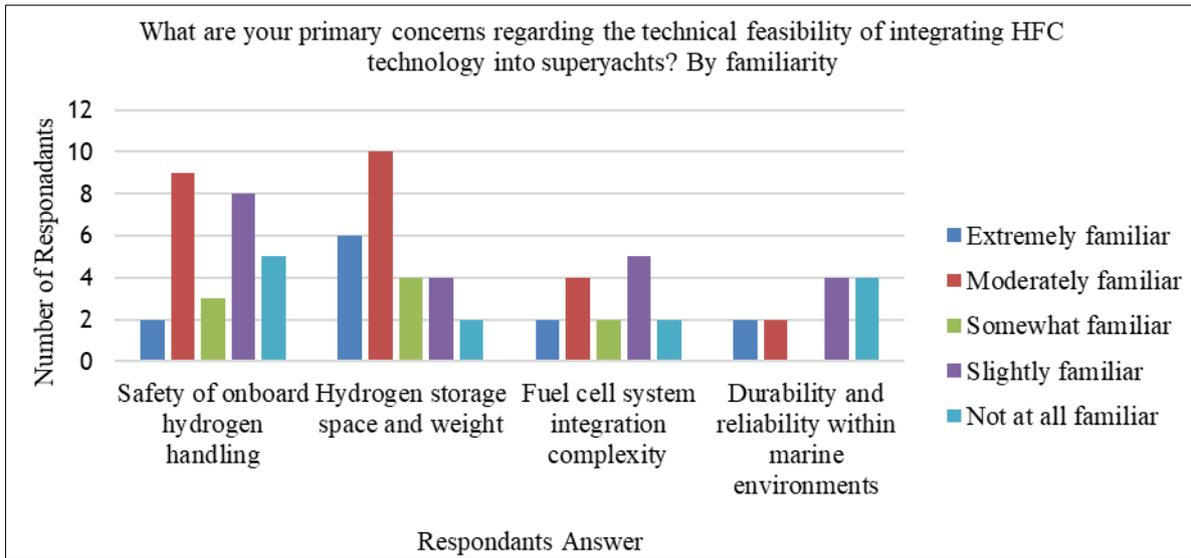
Within Figure 4, engineering officers and chief engineers predominantly consider client influence to be of “significant” or of “extreme” importance. Only a small minority report it as “not at all” or “slightly” significant.

3.1.3. Perceived Technical Challenges



Source: Mendoza

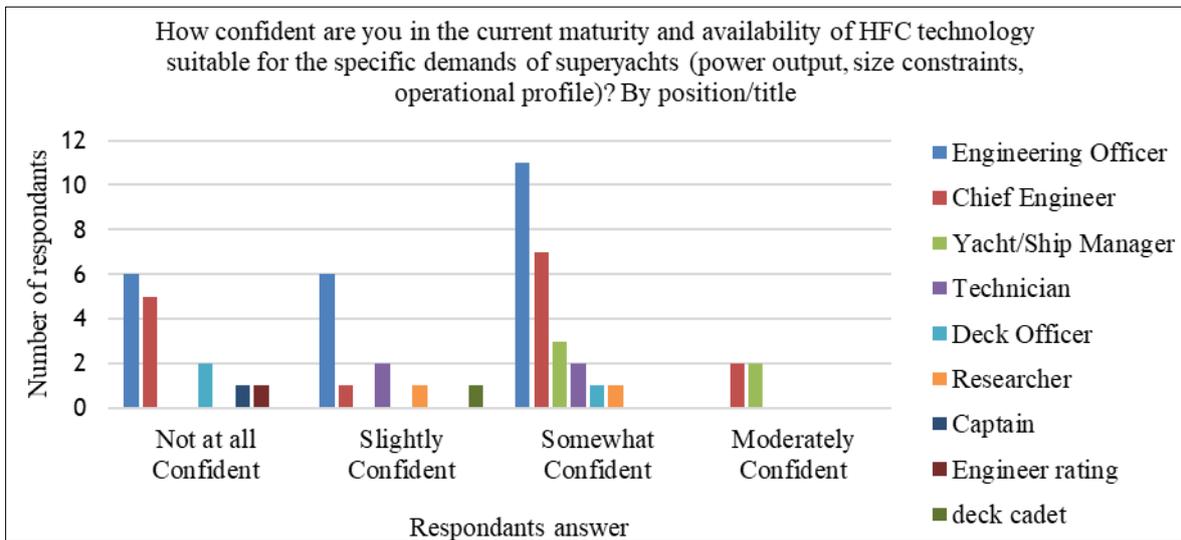
Figure 5 Primary concerns of technical feasibility, by position/title



Source: Mendoza

Figure 6 Primary concerns of technical feasibility, by familiarity

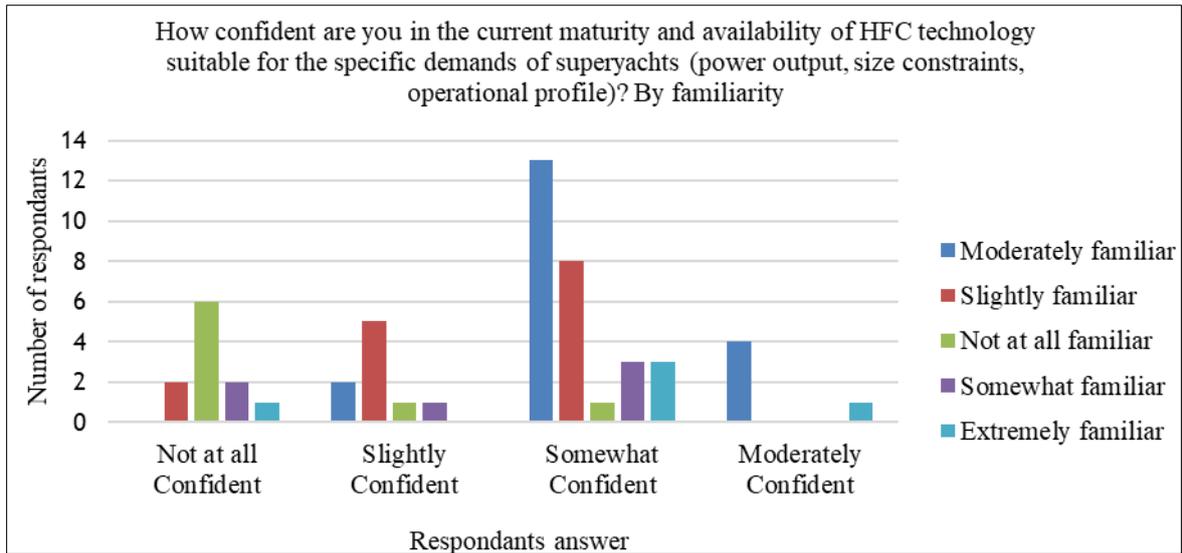
Analysis of Figure 5 demonstrates distinct differences in perceived challenges depending on professional roles and technology. Engineering officers express the highest level of concern regarding onboard hydrogen handling safety, as well as hydrogen storage space and weight considerations. Figure 6 highlights the more familiar participants prioritise the practical challenge of onboard storage and handling above general durability concerns.



Source: Mendoza

Figure 7 The confidence in the current maturity and availability of HFC technology, by position/title

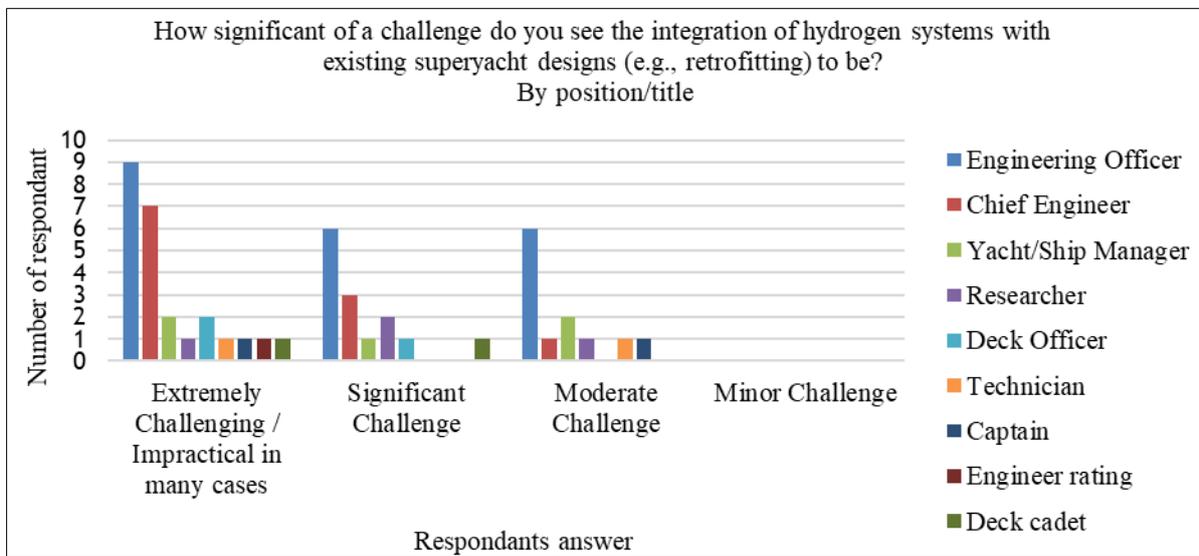
The analysis of Figure 7 reveals that professionals maintain moderate confidence levels regarding the current state of HFC technology for superyacht applications.



Source: Mendoza

Figure 8 Confidence in the current maturity and availability of HFC technology, by familiarity

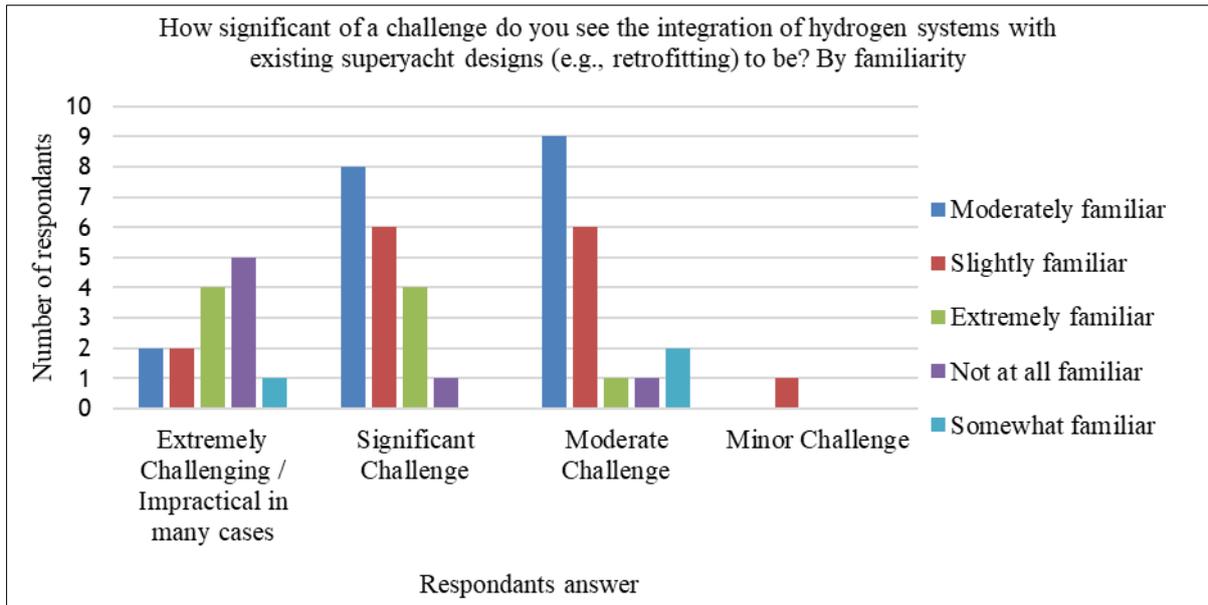
Figure 8 illustrates a direct relationship between familiarity and assurance, as participants who reported being “extremely familiar” showed the highest confidence in their technological readiness.



Source: Mendoza

Figure 9 Perceived challenge of integrating hydrogen systems with existing superyacht designs, by position/title

Engineering professionals have fostered a strong industry consensus, as shown in Figure 9, that retrofitting existing superyachts with hydrogen systems is a highly complex challenge.

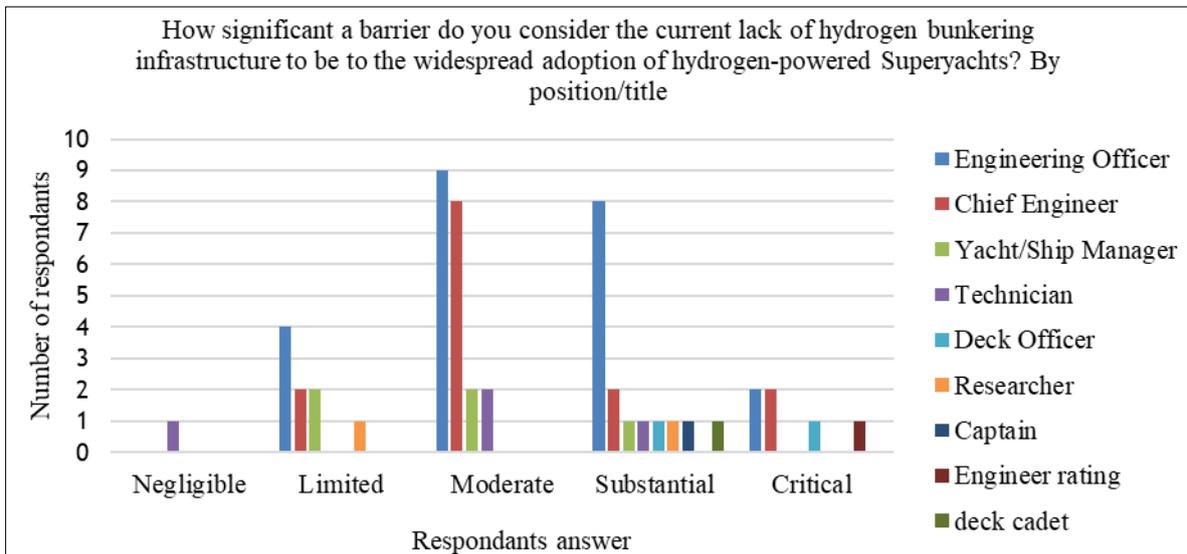


Source: Mendoza

Figure 10 Perceived challenge of integrating hydrogen systems with existing superyacht designs, by familiarity

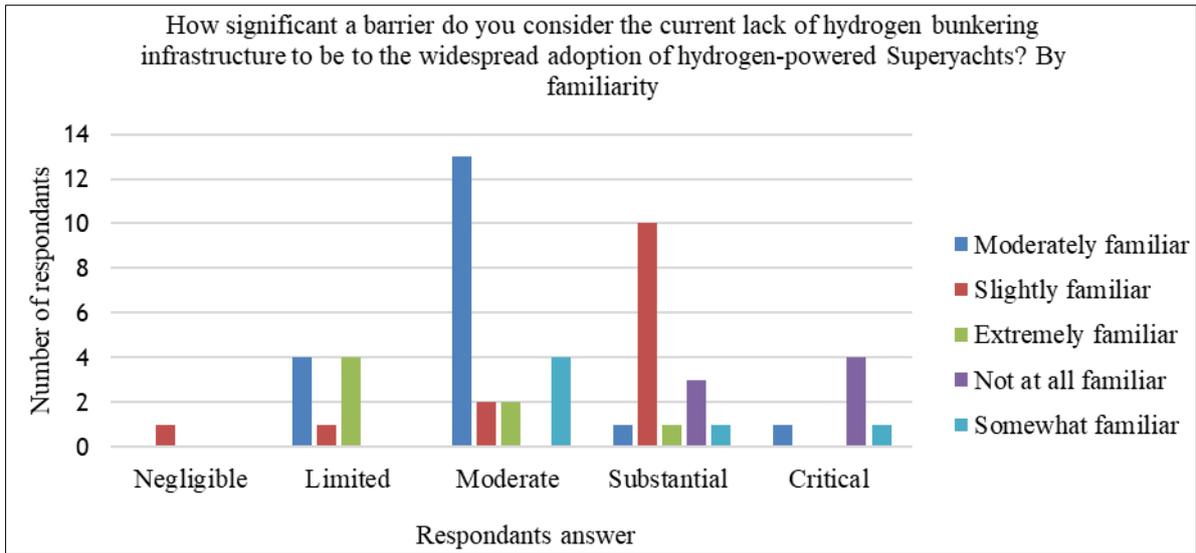
This shared understanding creates a sense of Community among experts and non-experts, as shown in Figure 10, who all recognize this task as challenging, regardless of their position/title or familiarity, as it represents a fundamental engineering issue.

3.1.4. Perception of Infrastructures and Bunkering



Source: Mendoza

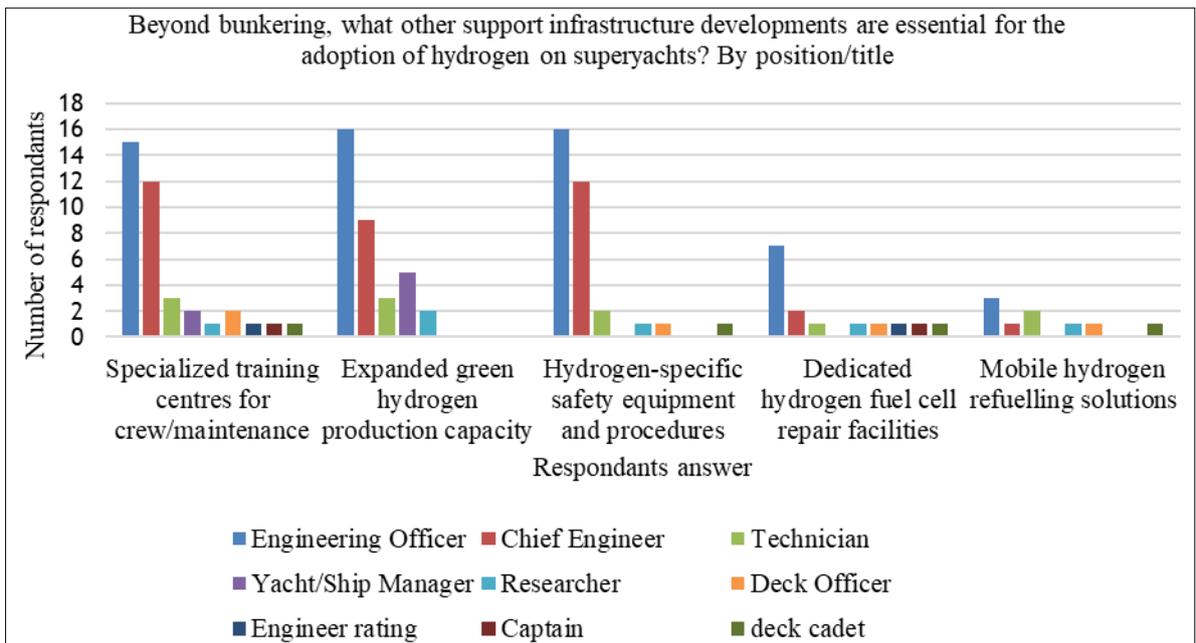
Figure 11 Perceived view of hydrogen bunkering infrastructure, by position/title



Source: Mendoza

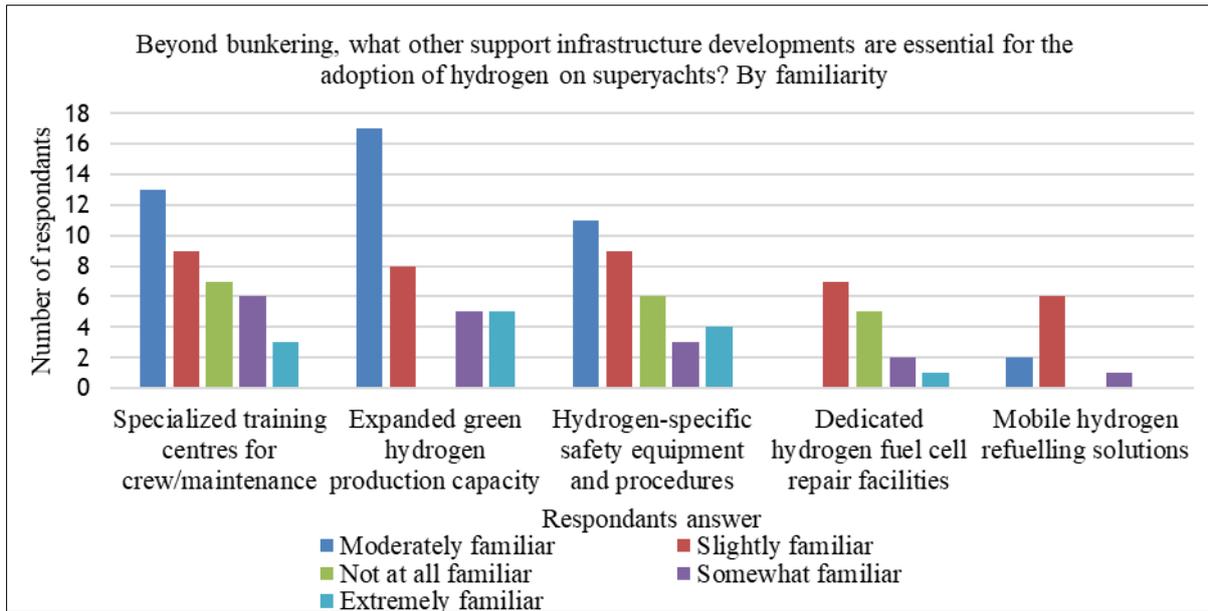
Figure 12 Perceived view of hydrogen bunkering infrastructure, by familiarity

According to Figure 11, the absence of hydrogen bunkering facilities represents a “moderate” obstacle to the broad adoption of hydrogen-powered superyachts. Engineers view the lack of hydrogen bunkering infrastructure as a “moderate” or “substantial” issue. However, individuals who are “not at all familiar” with the technology rate it as a “critical” barrier, as shown in Figure 12.



Source: Mendoza

Figure 13 Perceived essential support infrastructure requirements, by position/title

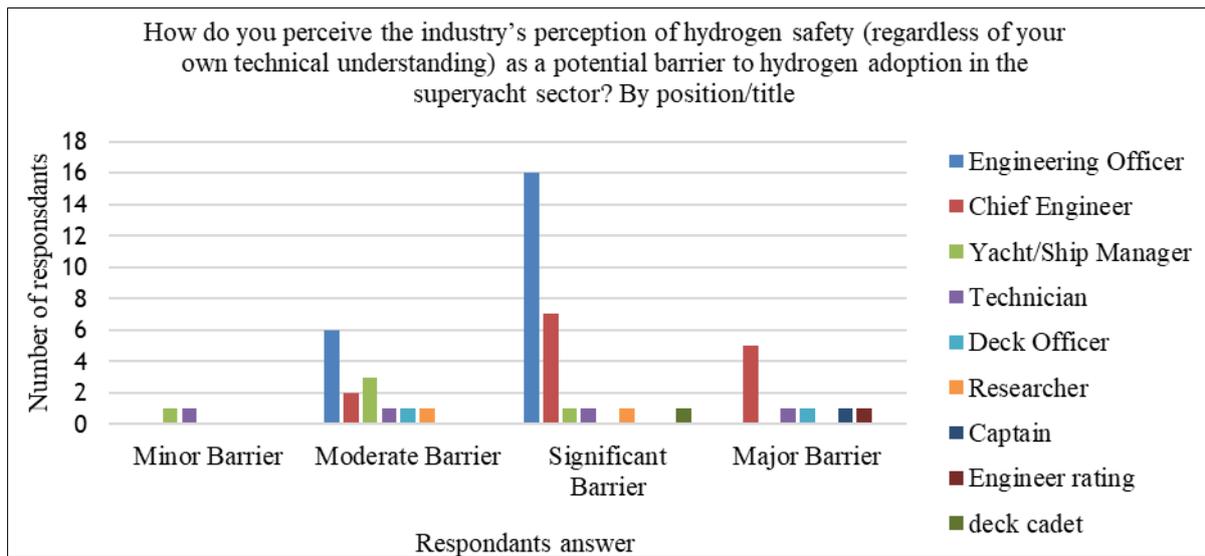


Source: Mendoza

Figure 14 Perceived essential support infrastructure requirements, by familiarity

Findings from both Figures 13 and 14 display essential infrastructural requirements that extend beyond bunkering operations. “Specialised training centres” and “green hydrogen production capacity” receive consistent priority from both positions/title and familiarity levels. Figure 13 shows that “Engineering officers” also perceive “hydrogen-specific safety equipment and procedures” as a necessary development.

3.1.5. Perception of Safety



Source: Mendoza

Figure 15 Perception of hydrogen safety, by position/title

In Figure 15, "engineering officers" primarily view hydrogen safety as a "significant barrier", but chief engineers place their views between "significant" and "major" barriers. Yacht/ship managers and technicians demonstrate a wider range of perceptions that incorporate both "minor" and "moderate" barriers.

3.1.6. Perception of current industry and government collaboration

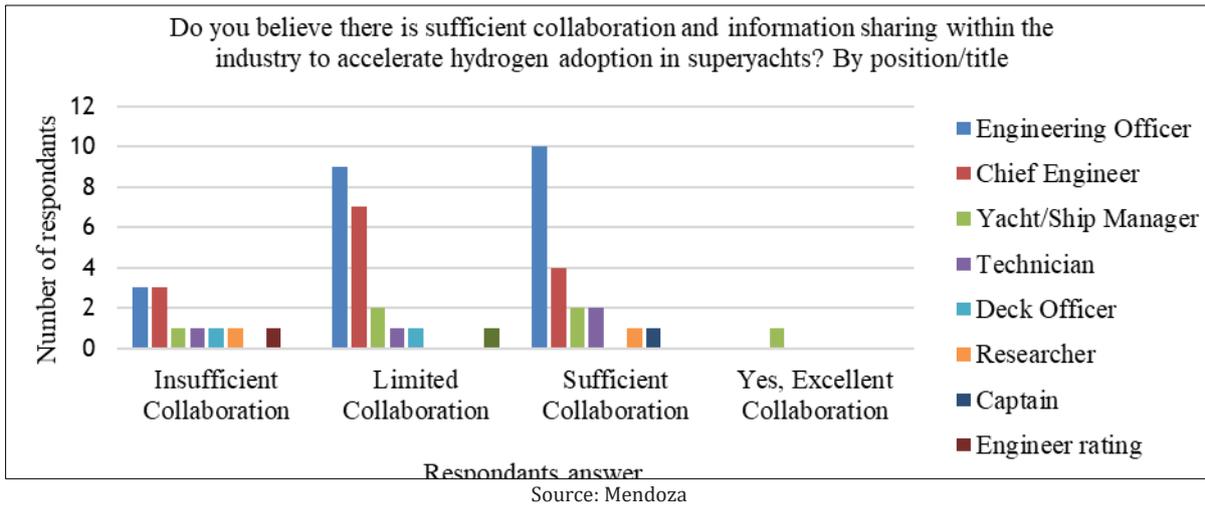


Figure 16 Perception of collaboration and information sharing within the superyacht industry, by position/title

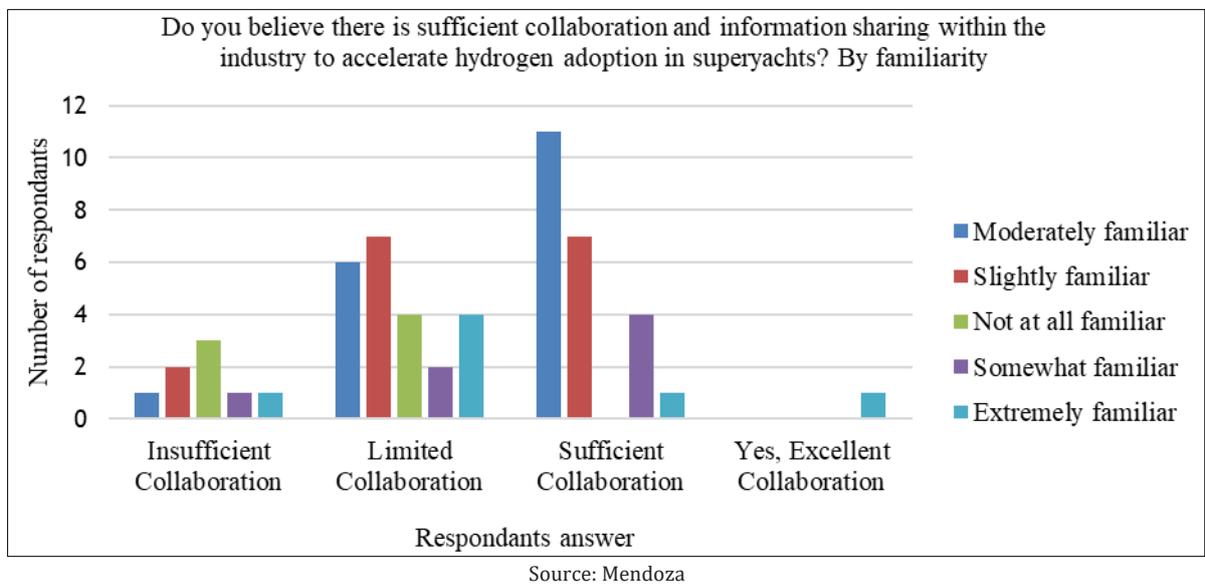
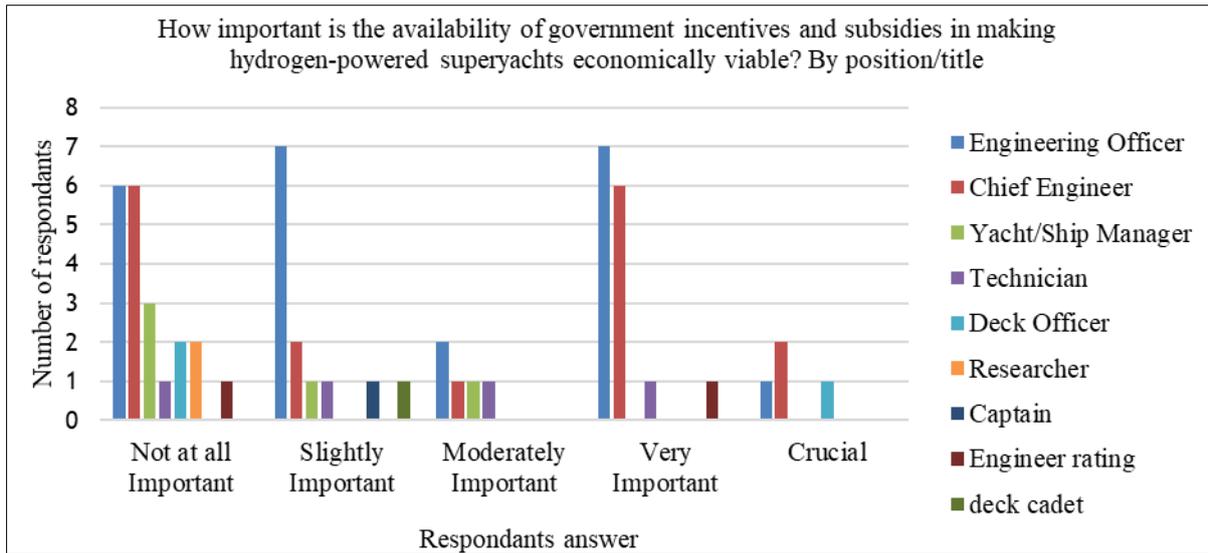


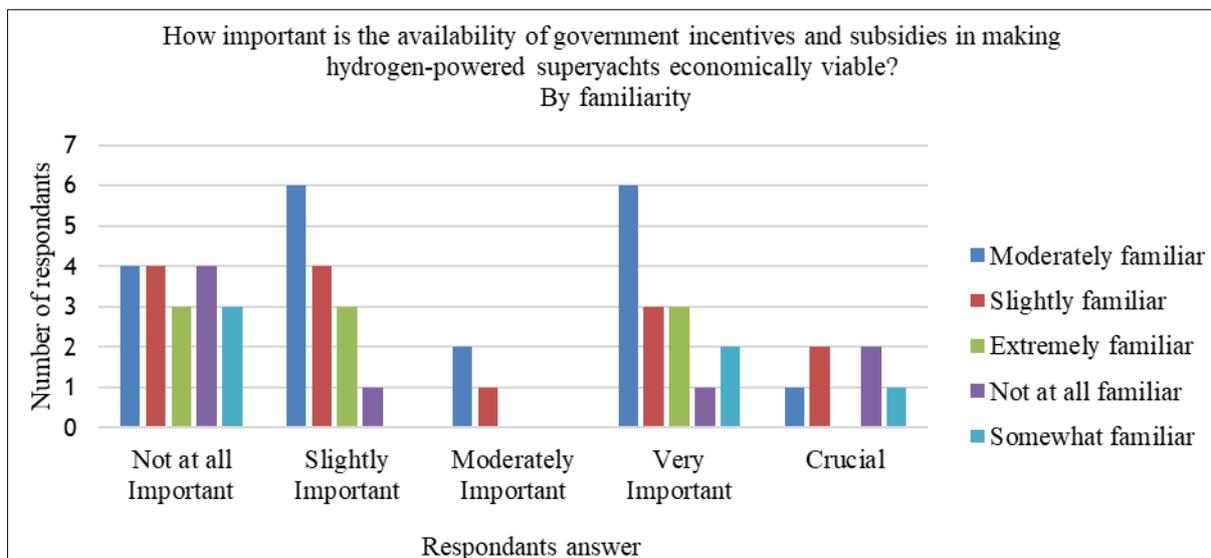
Figure 17 Perception of collaboration and information sharing within the superyacht industry, by familiarity

In Figure 16, Engineering Officers most often report “sufficient collaboration”; they also share the view of “limited collaboration” with chief engineers. The group of respondents who reported “not at all familiar” in Figure 17 disproportionately identified collaboration as “insufficient” or “limited”. Industry responses reveal varied opinions regarding the adequacy of collaboration and information sharing.



Source: Mendoza

Figure 18 Perceived necessity of government incentives and subsidies, by position/title



Source: Mendoza

Figure 19 Perceived necessity of government incentives and subsidies, by familiarity

In Figures 18 and 19, Engineering Officers and those “moderately familiar” with the subject commonly see government incentives as “very important” or “slightly important”. Yet, numerous respondents from different roles and knowledge backgrounds believe such incentives are “not at all important.” Industry perspectives remain conflicted regarding the essential nature of government support.

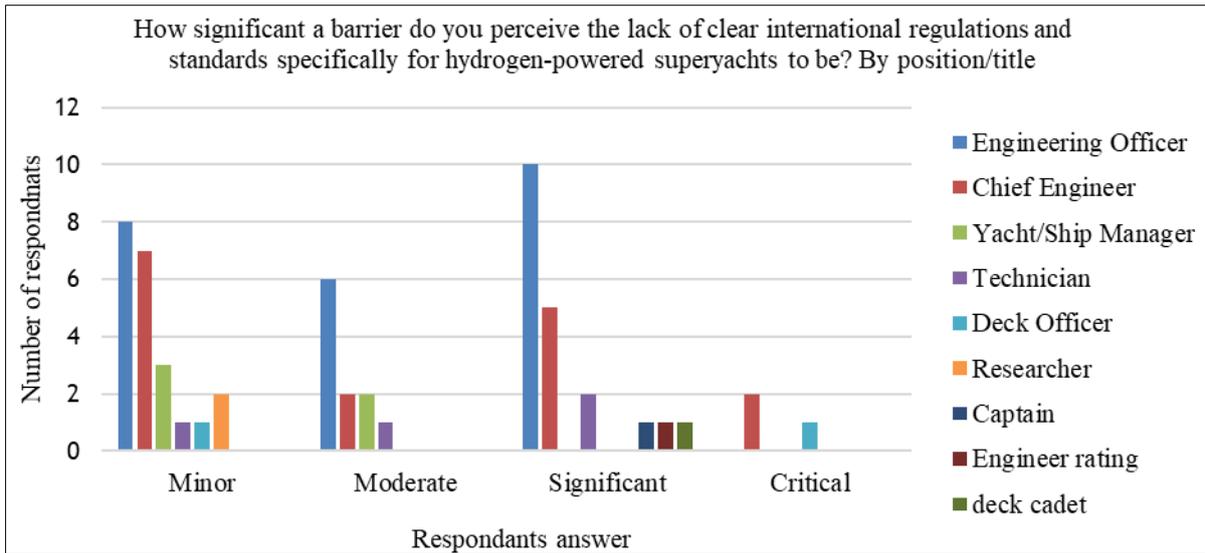


Figure 20 Perceived barrier due to the lack of clear international regulations, by position/title

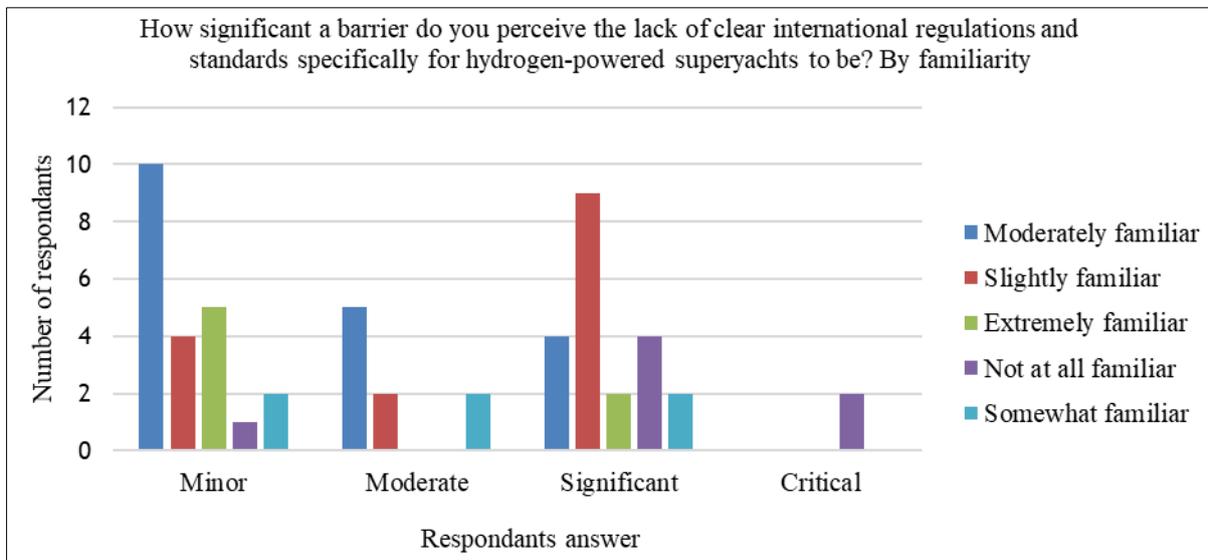
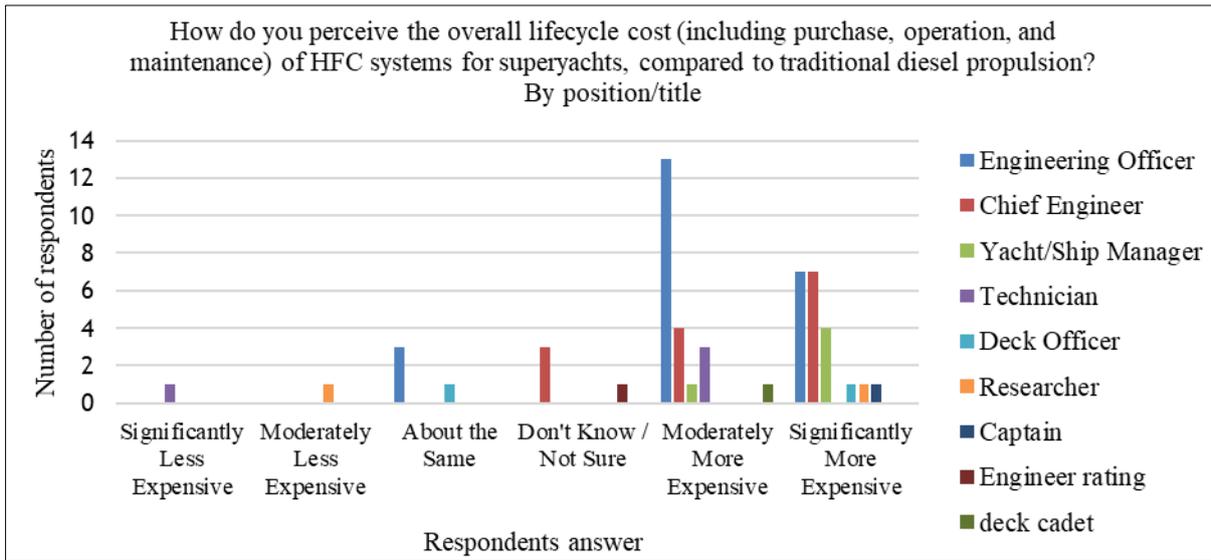


Figure 21 Perceived barrier due to the lack of clear international regulations, by familiarity

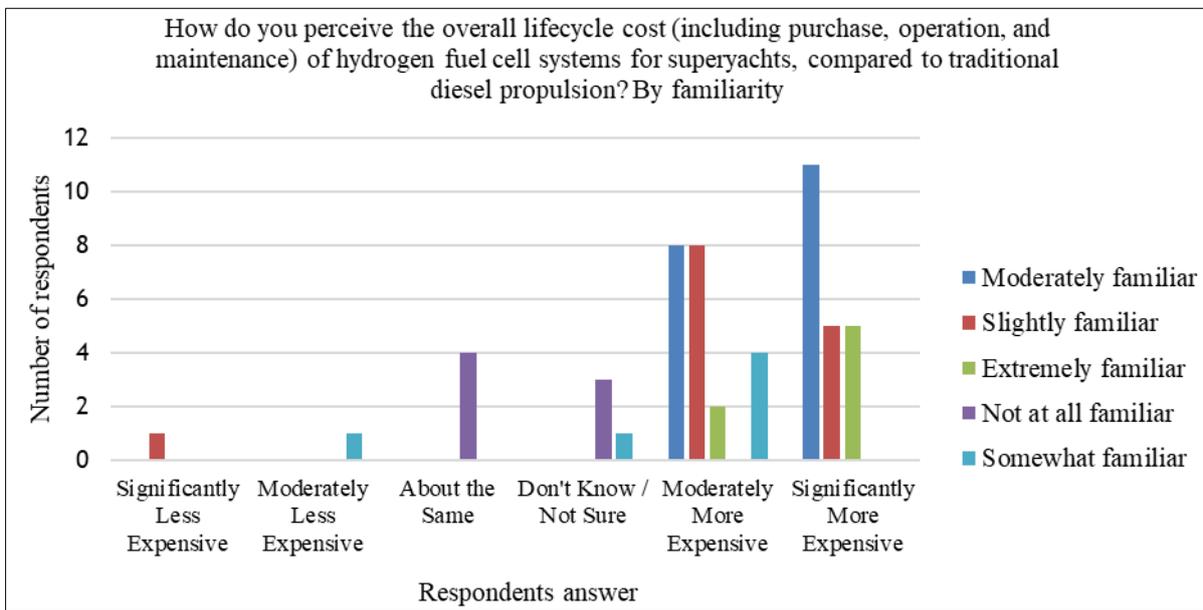
Figures 20 and 21 demonstrate that a diverse range of opinions exists regarding international regulations and standards. A significant portion of respondents across all familiarity levels and positions view the issue as "significant". In contrast, many Engineering Officers and respondents who are "moderately familiar" consider it to be minor. Those who identify as "not at all familiar" most commonly rate the lack of clear international regulations as "critical".

3.1.7. Feasibility and Viability



Source: Mendoza

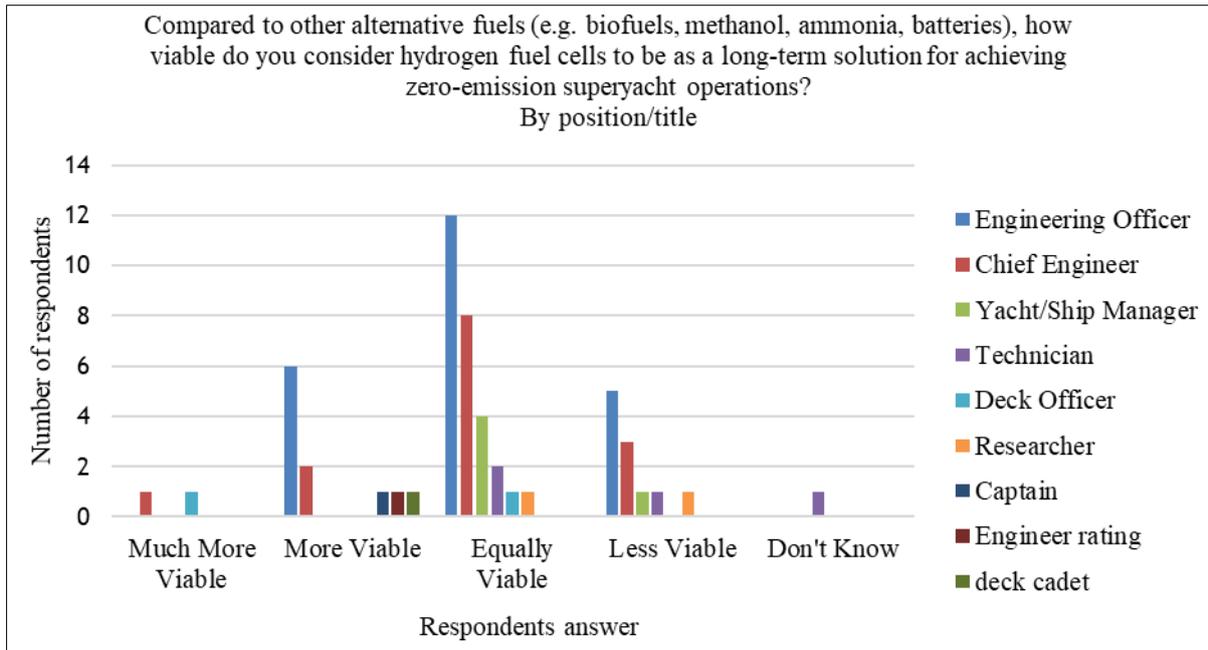
Figure 22 Perception of life-cycle cost, by position/title



Source: Mendoza

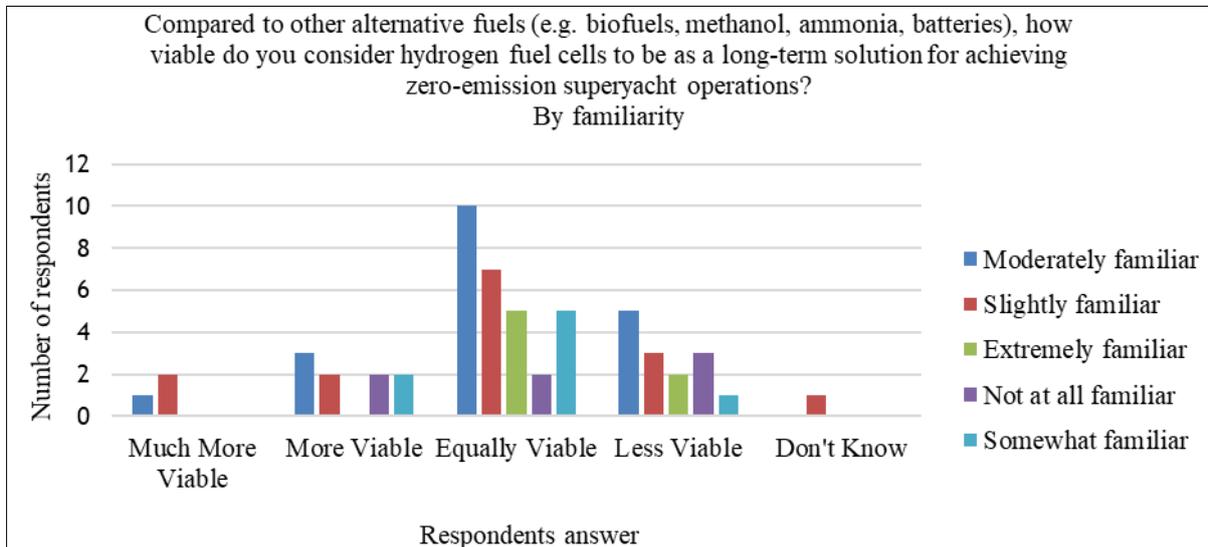
Figure 23 Perception of life-cycle cost, by familiarity

Across all professional levels and familiarity, the data underscore that HFC systems are consistently viewed as more expensive than diesel propulsion systems, as shown in Figures 22 and 23. Engineering officers, together with respondents who are moderately familiar, strongly agree with this opinion. Respondents who lacked familiarity frequently selected either "about the same" or "don't know/ not sure", highlighting their uncertainty of costs, as shown in Figure 23.



Source: Mendoza

Figure 24 Perception of hydrogen viability, by position/title



Source: Mendoza

Figure 25 Perception of hydrogen viability, by familiarity

The results in Figures 24 and 25 indicate a generally positive view of HFC viability, with only some mixed opinions. The response “equally viable” emerged as the dominant choice among all positions and levels of familiarity. Many engineering officers view hydrogen fuel cells as “more viable”, but numerous participants from diverse groups rate them as “less viable”, presenting varied perspectives on their competitive status among alternative fuels.

3.2. Interview results

Q1: From your perspective as a (Researcher and shipyard representative), what are the most significant technical hurdles of integrating HFC systems onto superyachts, specifically concerning fuel storage and power distribution?

3.2.1. Interviewee 1:

The primary obstacle is allocating sufficient "space that you need to put into the ship" for cryogenic hydrogen storage tanks. The system demands "a lot of additional equipment", like "double wall piping" and proper "detection systems", which creates engineering difficulties.

3.2.2. Interviewee 2:

The primary issue facing hydrogen fuel is its "energy density problem", as hydrogen requires "six to seven times the same space" as diesel for equivalent energy. Because hydrogen molecules are tiny, they tend to "escape" from storage containers, which creates material science challenges in containing them.

3.2.3. Interviewee 3:

Storing hydrogen demands substantial space because liquid hydrogen occupies "three to four times more" volume than diesel to deliver equivalent energy content. The need for larger storage space for hydrogen "reduces the range" and requires the removal of specific amenities, such as "gyms and guest bedrooms". The large volume needed for hydrogen storage has an impact on the "vessel's stability".

Q2: Considering the current market trends, how do you assess the economic viability of hydrogen as a fuel source for superyachts, particularly in comparison to traditional fuels and other alternatives?

3.2.4. Interviewee 1:

Production and transportation challenges make the economic feasibility of hydrogen uncertain. This shipyard has decided to adopt methanol as its fuel choice because it is a "commodity" that is simpler to "store and transport".

3.2.5. Interviewee 2:

The cost of hydrogen reaches levels that are "brutally expensive," reaching up to "ten times higher than diesel prices". The costs of installing "high safety tanks" along with custom manufacturing processes raise the overall expense. The gap between hydrogen and diesel fuel costs could narrow due to increasing diesel prices and the European Union's (EU) ETS.

3.2.6. Interviewee 3:

The economic appeal of hydrogen remains low because "production costs" and "location greatly affect its price". The absence of a unified global fuel market results in fluctuating prices, which become even more "unpredictable because of the EU ETS". The future acquisition of fuels will be dependent on their "carbon intensity" levels.

Q3: Given the increasing focus on environmental sustainability, how do you believe the superyacht industry can effectively transition to hydrogen to minimise its carbon footprint?

3.2.7. Interviewee 1:

Superyacht transition initiatives stem from "innovative clients" because these vessels typically operate outside of "regulatory constraints". This shipyard "informs clients about emission reduction options". "Methanol is becoming the preferred" focus because of its potential for "worldwide uptake and scalability".

3.2.8. Interviewee 2:

The superyacht sector can "lead", due to the "moral incentive" of wealthy owners. Government incentives, including "fines for dirty fuels", have the potential to speed up these changes. The introduction of Bill Gates' "hydrogen-powered superyacht will work, others will follow".

3.2.9. Interviewee 3:

A "more detailed policy or standard for vessel design, and also production" is needed. Classification societies' "cooperation" with yacht shipyards and policymakers is required to achieve the necessary results. "Learning from using the vessel with alternative fuel" is crucial for refining standards.

Q4: From an industry perspective, what collaborative efforts or partnerships do you believe are essential to accelerate the development and adoption of hydrogen technology in the superyacht sector?

3.2.10. Interviewee 1:

Shipbuilders acting as "system integrators" need to collaborate closely with component manufacturers to achieve optimal results. It requires maintaining a close alignment with the advancements made by system manufacturers. This shipyard "participates in co-development" in research projects, learning from "other industries." There's a "consensus that for energy transition, things shouldn't be hidden because it slows it down."

3.2.11. Interviewee 2:

The "UK Maritime Decarbonisation Research Hub" demonstrates effective collaboration by bringing "shipbuilders together" with "energy sector professionals". This approach creates collaborative networks which enhance project sustainability. The ethical obligation of new designers towards sustainability further "promotes" collaborative efforts.

3.2.12. Interviewee 3:

Strong ties between organisations, such as "classification societies" and "yacht producers", are essential for success. They "need to collaborate physically to achieve their common goals together". The group embraces equipment manufacturers along with classification societies and policymakers from organisations such as the "IMO". The development of additional "breakthrough projects" is crucial for formulating policies on vessel production and usage.

Q5: What are your views on the current state of regulatory frameworks and classification society guidelines related to hydrogen-powered vessels, and what improvements are needed?

3.2.13. Interviewee 1:

Regulators and class societies so far have developed regulations that remain "vague", and updates are incremental. The general regulations currently in place "fail" to address the distinct demands of superyachts. This shipyard collaborates with classification societies to implement "alternative design scenarios" that ensure safety.

3.2.14. Interviewee 2:

Regulations are "a bit lacking, honestly". Both classification societies and regulators remain hesitant until there are enough users to adopt the system, a typical "chicken and egg scenario." Crew training "will lag" implementation. Current training requirements for the use of hydrogen onboard are "bespoke" and costly.

3.2.15. Interviewee 3:

There is "no clear and straightforward standard for designing a hydrogen-powered vessel". The current IGF code serves only as a fundamental requirement for carriers, but it does not apply to fuel-powered ships. Development through collaborative efforts and practical experience will create a "more detailed policy or standard" for both the design and production of vessels.

Q6: How do you perceive the role of research and development (RandD) in advancing hydrogen technology for superyacht applications, particularly in fuel cell efficiency and durability?

3.2.16. Interviewee 1:

RandD requires manufacturers to "co-develop" and engage in research projects. This shipyard embraces knowledge from "other industries" and stresses information sharing since it believes hiding data during the energy transition process only creates unnecessary delays. The use of multi-fuel tanks and "full direct current" ships represents innovative approaches to "reduce fuel consumption."

3.2.17. Interviewee 2:

The "volumetric energy density problem" requires RandD to develop alternative storage systems, such as "ammonia" and "solid matrix." Designers strive for top-tier equipment and technology, which creates better efficiency. "Human behaviour and perceptions" also contribute to optimising operations.

3.2.18. Interviewee 3:

"There is room to improve the efficiency of the fuel cell system". Laboratory measurements show a "60% efficiency", whereas actual field performance falls between "47% and 50%". RandD efforts need to focus on optimising fuel cell

performance within the "30-60%" operational load range. In addition, "learning from use" provides essential insights to improve safety standards.

Q7: Considering the unique operational profiles of superyachts, how can power management systems be optimised to maximise the efficiency and reliability of HFC systems?

3.2.19. Interviewee 1:

A power management system operating through a "hybrid solution," where fuel cells generate "base loads" and batteries supply peak power, is the best solution. Batteries can absorb "load changes" to preserve a "nice consistent level of operation" for fuel cells, thereby avoiding problems such as "flooding and poisoning."

3.2.20. Interviewee 2:

"Hybridisation systems are probably the way forward". During anchoring operations, electric propulsion with batteries receives power from an auxiliary generator set, such as one fuelled by ammonia, to recharge the batteries. The energy efficiency of vessels "increases when hull improvements reduce the vessel's overall resistance."

3.2.21. Interviewee 3:

Hybrid systems combining fuel cells with batteries present a "good solution". Fuel cells generate power for four hours each day, which is then stored in batteries. They can achieve peak performance at their "highest efficiency" as batteries balance and absorb "load fluctuations".

Q8: How do you anticipate the development of hydrogen bunkering infrastructure impacting the operational range and flexibility of superyachts?

3.2.22. Interviewee 1:

Superyachts face geographical limitations because bunkering options are currently leaving superyachts "confined to those places for now". Broader adoption requires enhanced availability through "production chain, scaling, and distribution" improvements.

3.2.23. Interviewee 2:

The high costs of hydrogen arise from insufficient infrastructure because hydrogen functions as a "bespoke product". The existing "chicken and egg scenario" requires demand to initiate the development of infrastructure. Building infrastructure remains essential to achieving better range and flexibility capabilities.

3.2.24. Interviewee 3:

The growth of hydrogen applications for land-based industries will drive improvements in bunkering infrastructure. Economic realism depends on establishing "pipelines" between production sites and ports. Extending hydrogen use in "public transport options, trains and road traffic" will decrease expenses, making maritime operations financially feasible.

Q9: From a design perspective, how do you balance the need for hydrogen storage capacity with the preservation of onboard amenities and passenger comfort?

3.2.25. Interviewee 1:

Storing hydrogen requires "huge tanks" that consume payload space. Designers continuously seek to increase passenger space because it "represents a high cost to owners." Designers select methanol because of the improved balance between storage space requirements and passenger amenities.

3.2.26. Interviewee 2:

The balance is "owner-dependent". Superyachts typically maintain most amenities, regardless of necessity and size. Future tech advancements should "reduce space" requirements.

3.2.27. Interviewee 3:

Hydrogen storage needs three to four times the space used by diesel, which forces designers to make trade-offs that eliminate a gym or a guest's bedroom. The battery cooling systems used in hybrid versions require additional space. Crew space requirements are dependent on the designers' and owners' decisions.

Q10: How do you see owner and guest perception of hydrogen safety influencing its adoption in the superyacht industry, and what measures can be taken to address potential concerns?

3.2.28. Interviewee 1:

The interviewee shifted focus to regulatory and company safety practices while avoiding direct discussion about owner and guest perceptions of safety.

3.2.29. Interviewee 2:

The Hindenburg disaster has shaped public opinion and established a lasting educational legacy. Hydrogen is "safer than diesel" as it "doesn't pool on the floor" and "flashes off" quickly. Safety features, such as "double jacketing," ensure that hydrogen systems operate with extremely high safety standards. As adoption progresses incrementally, it will establish a "normal" level of acceptance.

3.2.30. Interviewee 3:

People tend to view hydrogen as "more dangerous" compared to diesel fuel. "Higher safety standards" are implemented to ensure that safety levels remain consistent. Owners and users must understand that higher safety standards are applied to hydrogen despite its perceived danger. The public's acceptance of hydrogen technology parallels their acceptance of "dangerous activities such as air travel, which now seems normal."

4. Discussion

The superyacht industry, a prominent symbol of luxury, is undergoing increasing demands for decarbonisation. The substantial environmental impact of the industry, combined with pending strict regulatory measures, including the IMO's 2050 net-zero goal, generates this pressure. The technological advancement of hydrogen fuel cells presents a zero-emission solution for this environmental context. This discussion will identify major themes from literature, survey and interview data while analysing barriers that affect hydrogen adoption across this industry. This exploration will cover the industry's knowledge of the technology alongside major technical obstacles, infrastructure shortcomings, financial feasibility concerns and the existing regulatory framework.

4.1. Familiarity and Perceived Demand

The study's findings demonstrated an apparent disparity in familiarity with hydrogen technology among various professional roles. According to the survey results, engineering professionals exhibit substantially greater knowledge than deck crew members. Despite this knowledge gap, a powerful consensus exists across all positions and levels of familiarity. The market is experiencing an increase in demand for sustainable superyachts. The growing demand for green superyachts stems from market dynamics rather than solely regulatory compliance.

Stakeholders regard client influence as highly important when adopting new technologies, with most rating it as "significant" or "extreme". Interviews verified that the drive for sustainable options stems from forward-thinking clients and green-minded owners who feel a "moral incentive". The evidence shows that end-users serve as key drivers for change, which makes it vital for shipyards and designers to develop sustainable options, such as hydrogen.

4.2. Perceived Technical Challenges: A Triad of Hurdles

The path to hydrogen adoption is hindered by a triad of technical challenges: Storage, technology maturity, and safety. Storage and integration stand out as the most significant practical challenges due to hydrogen's low volumetric energy density. The collected survey and interview data demonstrate that hydrogen storage requires up to seven times the volume of diesel, which negatively impacts vessel design, eliminates amenities, and presents severe retrofitting obstacles for existing yachts.

Stakeholders showed moderate confidence levels in technology maturity yet displayed improved confidence as familiarity increased, which indicates a knowledge gap leads to reluctance. The performance gap from laboratory

efficiency (60%) to real-world applications (47-50%) demonstrates a documented need for further research and development to improve operational reliability.

Perceptions related to safety create a significant psychological barrier. The negative public perception of hydrogen fuel, stemming from the Hindenburg disaster, contrasts with expert opinions, which suggest that hydrogen is safer than diesel because it dissipates quickly. Utilising hydrogen safely requires the implementation of higher safety standards, along with new training protocols, according to research literature that identifies new seafarer competencies as necessary.

4.3. Infrastructure and Bunkering: The 'Chicken and Egg' Scenario

The lack of sufficient hydrogen bunkering facilities emerged as a fundamental barrier to broad adoption. Both survey participants repeatedly identified this as a significant hurdle. Interviewees stated that the absence of refuelling ports creates substantial operational challenges, which force pioneering hydrogen yachts to operate exclusively in locations where fuel is accessible. This situation is trapped in a classic “chicken and egg scenario.” The expansion of infrastructure relies on established demand, but demand will not develop without improved infrastructure.

The infrastructure obstacles faced by hydrogen vessel adoption extend far beyond the need for bunkering ports. Stakeholders demonstrate advanced insights from survey data, which highlights the need for a comprehensive support framework. Survey participants repeatedly emphasised that Specialised training centres, along with adequate green hydrogen production capacity, must exist before further adoption can take place. The response indicates that stakeholders comprehend that the availability of hydrogen alone does not meet the complete requirements for successful deployment.

The sector requires competent personnel trained in safe fuel handling, as well as dependable supplies of sustainably produced green hydrogen, to ensure this technology delivers its maximum environmental advantage safely. Hydrogen cannot achieve mainstream adoption without a supportive, integrated ecosystem and will, therefore, remain limited to niche, experimental applications.

4.4. Economic Viability and Cost

Industry experts agree that HFC systems cost significantly more than conventional diesel propulsion systems. The survey demonstrated that most respondents view the technology as considerably more expensive, which aligns with an interviewee's blunt judgment that hydrogen fuel is "brutally expensive." In addition to the high fuel costs, increased expenses include specialised storage tanks and fuel cells, as highlighted in the literature.

Economic viability evaluations remain complex despite the substantial expenses involved. According to researchers, viability depends on external financial mechanisms. Although the survey results displayed divided opinions about the need for governmental support, those interviewed proposed that EU ETS policies could narrow the cost differential between hydrogen fuel and diesel. The experts pointed out that directed subsidies could accelerate the transition process. Some industry leaders adopt practical solutions to navigate challenging economic conditions. An interviewee explained that their shipyard's current focus on methanol as a hydrogen storage medium represents a more sensible choice. The simplicity of methanol storage and transportation makes it an economical interim solution for progressing towards decarbonisation today.

4.5. The Regulatory and Collaborative Landscape

Survey results and interview responses revealed that international regulations create substantial obstacles, as interview participants labelled current standards as “vague” and “lacking.” The issue discussed is illustrated by actual events, which demonstrate how MAN Energy Solutions encountered obstacles securing approval for their liquid hydrogen tank design on Project 821 due to insufficient IGF code regulations.

The regulatory delay results in another “chicken and egg scenario,” where classification societies and regulators delay rule development until more vessels become operational, as reported by interviewees. To break this impasse, collaboration is essential. Participants in the survey expressed diverse opinions about current industry collaboration levels, yet interview results revealed a complete consensus regarding its crucial role. Industry experts from all disciplines concluded that strong collaborative partnerships between shipbuilders, classification societies, equipment manufacturers, and policymakers represent the sole route to establishing the necessary robust standards for progress.

4.6. Hydrogen as Part of a Broader Sustainability Strategy

The findings suggest that hydrogen should be considered an integral component within a broader decarbonisation strategy rather than a standalone solution.

Survey results demonstrate that hydrogen ranks equally viable among alternative fuels for most respondents, while many engineers categorise it as more feasible. It suggests confidence in its long-term potential.

The interviews produced a strong consensus endorsing hybrid solutions as the most effective and practical direction forward. Experts identified that combining fuel cells with batteries leads to enhanced power management optimisation. The fuel cells deliver constant, efficient baseload power, while the battery banks manage fluctuating peak loads. Combining these system components improves performance and protects fuel cells from flooding and poisoning, which could cause potential damage. This engineered hybrid solution effectively combines the advantages of both technologies to address hydrogen's inherent challenges, enhancing its feasibility for future applications.

4.7. Summary

The superyacht industry regards hydrogen as a long-term solution for decarbonisation; however, it faces immediate adoption delays due to the numerous difficulties discussed earlier in this study. Research reveals significant challenges related to technological maturity and integration, including inadequate infrastructure and support, regulatory delays, and excessive costs. These challenges require substantial innovation to be resolved. The entire superyacht industry, including owners, designers, shipyards, and regulators, will need to make a unified, active, and cooperative effort.

Abbreviations

The following abbreviations are used in this manuscript

- ALS: Air Lubrication Systems
- CAPEX: Capital Expenditure
- CCS: Carbon Capture Systems
- CH₂: Compressed Hydrogen
- CMDC: Clean Maritime Demonstration Competition
- CO₂: Carbon Dioxide
- ESD: Emergency Shut Down
- ETS: Emissions Trading Scheme
- EU: European Union
- FC: Fuel Cell
- Fuel EU: Refers to the Fuel EU Maritime regulation (a European Union regulation affecting shipping)
- GHG: Greenhouse Gas
- GT: Gross Tonnage (used for vessel size measurement)
- HFC: Hydrogen Fuel Cell
- HSFO: High Sulphur Fuel Oil
- ICE: Internal Combustion Engines
- IGF: International Code of Safety for Ships using Gases or other Low-flashpoint Fuels
- IMO: International Maritime Organisation
- L-T PEM FC: Low-Temperature Proton Exchange Membrane Fuel Cells
- LCA: Lifecycle Cost Analysis
- LH₂: Liquid Hydrogen
- LNG: Liquid Natural Gas
- LOHC: Liquid Organic Hydrogen Carrier
- LOA: Length Overall
- MDS: Maritime Decarbonisation Strategy
- MGO: Marine Gas Oil
- MJ: Megajoule (1,000,000 Joules)
- MJTTF: Maritime Just Transition Task Force
- MPA: Marine Protected Area
- NO_x: Nitrogen Oxides
- OPEX: Operational Expenditure
- PAH: Polycyclic Aromatic Hydrocarbons

- PEM: Proton Exchange Membrane
 - RandD: Research and Development
 - SOX: Sulphur Oxides
 - STCW: Standards of Training, Certification and Watchkeeping for Seafarers
 - UK ETS: United Kingdom Emissions Trading Scheme
 - VLSFO: Very Low Sulphur Fuel Oil
 - ZEVI: Zero Emission Vessels and Infrastructure
-

5. Conclusion

This study examined the substantial gap between the theoretical decarbonization capabilities of hydrogen fuel for the superyacht industry and its actual deployment. The study investigated adoption barriers from the perspectives of industry professionals to create a strategic path forward based on their shared knowledge. This study employed a mixed-methods research approach, incorporating broad surveys and detailed interviews, to provide a comprehensive analysis of the key challenges and opportunities.

Revisiting the Research Objectives

The study fulfilled its five objectives. It revealed that familiarity and knowledge of hydrogen technology is strongly linked to technical roles, which focus primarily on the significant challenges of onboard fuel storage, safe handling procedures and system integration.

Research into supporting infrastructure identified bunkering facility shortages as a critical barrier. Stakeholders demonstrated the requirement for specialised training and green hydrogen production as essential for further adoption.

Research revealed broad dissatisfaction with current regulatory frameworks. Survey data showed divided opinions on cooperative efforts. However, qualitative insights indicated a strong demand for more effective, forward-thinking partnerships.

Hydrogen systems require greater economic investment than diesel systems. Government incentives are lacking, with stakeholders expressing mixed views regarding their necessity.

The study concluded that owner perception remained a key driver for transition, which requires addressing public safety concerns through educational efforts and strict standards.

Implications for the Superyacht Industry

Significant consequences for the superyacht industry emerge from this study's findings. Hydrogen adoption represents a systemic challenge rather than an isolated engineering challenge. The process extends beyond simply replacing engines, as it alters vessel design and operational procedures while also demanding new port facilities and advanced crew training.

The system-wide nature of hydrogen adoption establishes the second main implication, which is the essential need for collaborative efforts. The industry requires all stakeholders to collaborate, as waiting for one company or organisation to provide solutions is not an option. The advancement of standards depends on cooperative efforts from shipyards and designers, classification societies and flag states, and fuel suppliers to jointly develop standards and exchange knowledge from pilot projects while sharing early adopter risks and benefits.

The effectiveness of advanced maritime technology is highly influenced by the competency and performance of its operating crew. The study demonstrates the urgent need for the industry to develop a new standardised training framework. The most advanced hydrogen systems cannot achieve safe and zero-emission operations without a skilled and confident crew to manage them.

Limitations and Future Research

The study faced multiple limitations stemming from its chosen methodology. This study used a specific sample size, which, despite its diversity, limits its applicability to the global superyacht industry. The analysis relies on professionals' subjective views rather than factual operational data, which opens the possibility for personal biases to influence the

results. The study provides a temporary perspective, as hydrogen technology and regulations are developing rapidly, which means perceptions will likely evolve as the industry progresses.

Future research paths become evident from these limitations

- Stakeholders require a quantitative Lifecycle Cost Analysis (LCA) to obtain factual data on the long-term economic benefits of hydrogen compared to other fuels.
- Longitudinal research on pioneering vessels, such as Feadship's Project 821, would provide essential empirical data regarding their performance and maintenance issues while revealing real-world reliability insights.
- Immediate research efforts should focus on creating standardised training and certification guidelines for crew operating hydrogen-powered superyachts to uphold safety standards and competence throughout the fleet.
- Understanding the viewpoints of superyacht owners and charter clients through a dedicated study will reveal essential demands and specific concerns, guiding future industry strategies.

Concluding remarks

The superyacht industry combines its innovative culture with customisation capabilities and substantial financial resources to stand out as a leading force for future maritime developments. Research findings indicate that industry professionals possess a comprehensive understanding of the significant challenges associated with adopting hydrogen. The way forward presents challenges yet remains clearly defined. The sector can make sustainable luxury yachting a practical, zero-emission reality by working together to overcome the technical, infrastructural, economic, and regulatory barriers identified in this study. Thereby successfully "fuelling the future."

Recommendations

The study presents actionable recommendations to promote the secure implementation of HFC technology within the superyacht industry.

Establish a Cross-Industry Hydrogen Task Force

- **Why:** The study demonstrates that both regulatory delays and infrastructure shortfalls present a "chicken and egg" dilemma, which exceeds the resolution abilities of individual corporations. All interviewees agreed that collaboration is necessary to resolve this deadlock.
- **Recommendation:** Leading shipyards, classification societies, and technology providers, alongside flag states and owner representatives, need to establish a specialised task force for superyacht hydrogen adoption.
- **Implementation:** The primary responsibility of the task force should be to jointly create proposed standards for vessel design, as well as safety protocols and bunkering procedures. After developing unified standards, these should be submitted to the IMO and individual flag states to accelerate the formal regulatory process. The task force should establish a framework to share anonymised operational data from pilot projects to promote industry-wide learning and foster trust.

Develop a Standardised Crew Competency Framework

- **Why:** The survey findings identified safety concerns as a primary barrier, while the literature review and interviews revealed a significant deficiency in crew training. Survey participants identified specialised training centres as a top priority.
- **Recommendation:** The industry must transition from expensive individual training courses to establish an internationally accepted, standardised training endorsement for engineers and crew who operate hydrogen-powered superyachts.
- **Implementation:** Shipyards and system manufacturers must collaborate with maritime training institutions to develop Standards of Training, Certification and Watchkeeping for Seafarers (STCW) approved courses. These will enhance management's competency in handling the specific characteristics of hydrogen and emergency procedures. Seafarers will gain confidence and safety skills while establishing a defined career path through this initiative.

RandD efforts should prioritise advancements in storage density alongside the optimisation of hybrid systems

- **Why:** Across all the data sources examined, the requirement for volumetric space for hydrogen storage became the most repeatedly mentioned technical obstacle. Experts interviewed identified hybrid power systems as the most practical and efficient solution for the near future.

- **Recommendation:** Targeted research and development efforts in hydrogen storage efficiency, hybrid fuel cell batteries, and power management systems demand industry-wide funding.
- **Implementation:** Publicly funded sources, such as the UK's ZEVI fund, in conjunction with a collaborative RandD consortium comprising shipyards, universities, and technological specialists, will facilitate resource sharing for accelerated innovation in key sectors.

Compliance with ethical standards

Acknowledgments

The authors extend their heartfelt thanks to the 53 survey respondents for donating their time and to the three interviewees whose deep insights into the superyacht industry proved highly valuable.

The authors would like to thank Southampton Solent University for providing the necessary resources and environment that enabled this study to reach a successful completion.

The authors owe a profound thank you to their friends and family members (especially to their mother) for their enduring patience and support throughout this entire journey. Your support has been truly exceptional.

Disclosure of conflict of interest

The authors declare no conflicts of interest.

Statement of informed consent

Informed consent was obtained from all subjects involved in the study.

Author Contributions

“Conceptualization, H.M; methodology, H.M; software, H.M; validation, H.M; formal analysis, H.M; investigation, H.M; resources, H.M; data curation, H.M; writing—original draft preparation, H.M; writing—review and editing, H.M and M.B; visualization, H.M; supervision, M.B; project administration, H.M and M.B; funding acquisition, NA.

All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Data Availability Statement

Data are available from the corresponding author.

References

- [1] L'ECHONAUTIQUE, 2024. Is Hydrogen an Ultimate Solution for A Greener Yachting Industry? France: [viewed 17 July 2025]. Available from:
- [2] <https://www.echonautique.com/how-hydrogen-could-be-the-future-of-the-yachting-industry/>
- [3] BARROS, B. and R. WILK, 2021. The outsized carbon footprints of the super-rich. *Sustainability: Science, Practice and Policy*, 17(1), 316- 322
- [4] IMO, 2023. MEPC 80/17/Add.1 - 2023 IMO Strategy on Reduction of GHG Emissions from Ships. UK: IMO [viewed 17 July 2025]. Available from:
- [5] <https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/annex/MEPC%2080/Annex%2015.pdf>
- [6] ZHANG, C. et al., 2024. Technical Requirements for 2023 IMO GHG Strategy. *Sustainability*, 16(2024), 1-16
- [7] STARK, C. et al., 2022. Study on Applicability of Energy-Saving Devices to Hydrogen Fuel Cell-Powered Ships. *Journal of Marine Science and Engineering*, 10(3), 1-33

- [8] ELAMMAS, T., 2023. Hydrogen Fuel Cells for Marine Applications: Challenges and Opportunities. *International Journal of Research in Advanced Engineering and Technology*, 9(1), 38-43
- [9] HICKLING, M., 2024. Hydrogen's Hurdles. UK: Superyacht news [viewed 17 July 2025]. Available from:
- [10] <https://www.superyachtnews.com/opinion/hydrogens-hurdles>
- [11] VAN HOECKE, L. et al., 2021. Challenges In the Use of Hydrogen for Maritime Applications. *Energy andamp; Environmental Science*, 14(2), 815-843
- [12] KOSTIDI, E. et al., 2025. Sustainable Fuel Supply for Very Small Island Transportation: The Potential of Hybrid Renewable Energy and Green Hydrogen. *Journal of Marine Science and Engineering*, 13(3), 1-18
- [13] SEA INDEX, 2025. Superyacht Decarbonisation: Leadership, Innovation and Future Fuels for a Sustainable Industry. Monaco: Sea Index [viewed 17 July 2025]. Available from:
- [14] <https://sea-index.com/superyacht-decarbonisation-leadership-innovation/>
- [15] LATAPÍ, M., B. DAVÍÐSDÓTTIR and L. JÓHANNSDÓTTIR, 2023. Drivers And Barriers for the Large-Scale Adoption of Hydrogen Fuel Cells by Nordic Shipping Companies. *International Journal of Hydrogen Energy*, 48(15), 6099-6119
- [16] KRANTZ, G. et al., 2023. Assessing the Environmental Impact of Eight Alternative Fuels in International Shipping: A Comparison of Marginal vs. Average Emissions. *Environments*, 10(9), 1-18
- [17] ANANTHARAMAN, M., A. SARDAR and R. ISLAM, 2025. Decarbonization of Shipping and Progressing Towards Reducing Greenhouse Gas Emissions to Net Zero: A Bibliometric Analysis. *Sustainability*, 17(7), 1-24
- [18] GOV UK, 2025. Maritime Decarbonisation Strategy. UK: Department for Transport [viewed 17 July 2025]. Available from:
- [19] <https://assets.publishing.service.gov.uk/media/67f4dcb3c2fea2548f4eff64/dft-maritime-decarb-strategy-25.pdf>
- [20] ALLIED MARKET RESEARCH, 2023. Superyacht Market Size, Share, Competitive Landscape and Trend Analysis Report, by Size, by Application, by Propulsion: Global Opportunity Analysis and Industry Forecast, 2023-2032. Allied market Research [viewed 16 July 2025]. Available from: <https://www.alliedmarketresearch.com/request-sample/A11376>
- [21] SUPERYACHTNEWS, 2025. The Superyacht Report. Netherlands: Dutch Design [viewed 18 July 2025]. Available from:
- [22] <https://www.superyachtnews.com/library/thesuperyachtreport/opensource/issuu/224>
- [23] MAN ENERGY SOLUTIONS, 2024. MAN Cryo Supplies Fuel System for World's First Hydrogen-Powered Superyacht. Germany: Everllence [viewed 17 July 2025]. Available from:
- [24] <https://www.man-es.com/company/press-releases/press-details/2024/06/24/man-cryo-supplies-fuel-system-for--world-s-first-hydrogen-powered-superyacht>
- [25] LLORET, J. and A. CARREÑO, 2020. Safeguarding marine protected areas in the growing mediterranean blue economy recommendations for leisure boating. Slovenia: [viewed 17 July 2025].
- [26] Available from:
- [27] https://www.researchgate.net/publication/348590748_SAFEGUARDING_MARINE_PROTECTED_AREAS_IN_THE_GROWING_MEDITERRANEAN_BLUE_ECONOMY_RECOMMENDATIONS_FOR_LEISURE_BOATING#fullTextFileContent
- [28] TAY, Z.Y. and D. KONOVESSIS, 2023. Sustainable Energy Propulsion System for Sea Transport to Achieve United Nations Sustainable Development Goals: A Review. *Discover Sustainability*, 4(1), 1-35
- [29] KARATUG, C., Y. ARSLANOGLU and C. GUEDES SOARES, 2022. Evaluation of Decarbonization Strategies for Existing Ships. *Trends in Maritime Technology and Engineering Vol 2. 2022*. London: CRC Press, pp: 45-54
- [30] WANG, Q., H. ZHANG and P. ZHU, 2023. Using Nuclear Energy for Maritime Decarbonization and Related Environmental Challenges: Existing Regulatory Shortcomings and Improvements. *International Journal of Environmental Research and Public Health*, 20(4), 1-24

- [31] GIL, Y. et al., 2013. Feasibility Study on Nuclear Propulsion Ship according to Economic Evaluation. Vienna: IAEA [viewed 16 July 2025].
- [32] Available from: <https://inis.iaea.org/records/66e82-y4035>
- [33] WANG, Z. et al., 2024. Status And Prospects in Technical Standards of Hydrogen-Powered Ships for Advancing Maritime Zero-Carbon Transformation. *International Journal of Hydrogen Energy*, 62(2024), 925-946
- [34] POURRAHMANI, H. et al., 2022. Progress In the Proton Exchange Membrane Fuel Cells (PEMFCs) Water/ Thermal Management: From Theory to The Current Challenges and Real-Time Fault Diagnosis Methods. *Energy Reviews*, 1(1), 1-24
- [35] BERKEHAN INAL, O., C. DERE and C. DENIZ, 2021. Onboard Hydrogen Storage for Ships: An Overview. 5th International Hydrogen Technologies Congress (IHTEC-2021), 1-10
- [36] GRAHN, M., S. BRYNOLF and M. TALJEGÅRD, 2017. Electrofuels or Hydrogen as Marine Fuel: A Cost Comparison. London: Shipping in Changing Climates (SCC), 1-8
- [37] SÜRER, M.G. and H.T. ARAT, 2022. Advancements And Current Technologies on Hydrogen Fuel Cell Applications for Marine Vehicles. *International Journal of Hydrogen Energy*, 47(45), 19865-19875
- [38] ISHAQ, H., I. DINCER and C. CRAWFORD, 2021. A Review on Hydrogen Production and Utilization: Challenges and Opportunities. *International Journal of Hydrogen Energy*, 47(62), 26238- 26264
- [39] CHENG, J., 2025. The Adoption of Hydrogen Fuel in Aviation: Incentives and Challenges for Decarbonization. *Highlights in Science, Engineering and Technology*, 119(2024), 16-22
- [40] LR, 2024. Seafarer Training in Need of Comprehensive Overhaul to Ensure Safe Decarbonisation of Shipping. UK: Lloyd's Register [viewed 16 July 2025]. Available from:
- [41] <https://www.lr.org/en/knowledge/press-room/press-listing/press-release/2024/seafarer-training-in-need-of-comprehensive-overhaul-to-ensure-safe-decarbonisation-of-shipping/>
- [42] ICS, 2024. Considerations Of Training Aspects for Seafarers on Ships Powered by Ammonia, Methanol and Hydrogen. UK: Maritime Just Transition [viewed 17 July 2025]. Available from:
- [43] https://www.ics-shipping.org/wp-content/uploads/2024/11/MJTTF-Report_Training-Aspects-for-Seafarers_Single-Spread_20241122.pdf