Article citation info:
Bilski M. Alternative energy sources and modern fuel stations for motor yachts. Combustion Engines. 0000;000(0):00-00. https://doi.org/10.19206/CE-211824

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Alternative energy sources and modern fuel stations for motor yachts

ARTICLE INFO

Received: 11 August 2025
Revised: 7 October 2025
Accepted: 8 October 2025
Available online: 13 October 2025

The yachting industry is undergoing a dynamic transformation driven by global environmental policies, technological advances, and rising societal awareness of sustainable transport. Conventional motor yachts powered by fossil fuels contribute significantly to greenhouse gas emissions and local pollution, prompting increasing interest in alternative propulsion technologies. This article examines two of the most promising solutions – electric propulsion and hydrogen fuel cells – focusing on their technical characteristics, economic feasibility, and environmental impacts. A methodological framework was developed to assess modern fuel station infrastructure for motor yachts, applying criteria such as availability, safety, energy efficiency, and regulatory compliance. Life-Cycle Costing (LCC), Net Present Value (NPV), and Life Cycle Assessment (LCA) analyses were conducted to compare the long-term economic and ecological performance of electric charging and hydrogen refuelling stations. Case studies from Europe, North America, and Asia illustrate the rapid expansion of alternative fuel infrastructure, ranging from high-power DC charging and wireless inductive systems to containerised hydrogen stations integrated with renewable energy sources. The results demonstrate that electric propulsion is best suited to short-distance recreational navigation, while hydrogen offers advantages for long-range and intensive applications. The study concludes that both technologies will likely coexist as complementary solutions, with investment potential concentrated in tourist-intensive waterfronts and urbanised port areas. Future prospects include innovations in wireless charging, local green hydrogen production, and hybrid infrastructure, reinforcing the role of marinas as active players in the maritime energy transition.

Key words: *alternative energy sources, motor yachts, electric propulsion, hydrogen fuel cells, marina infrastructure*

1. Introduction

The yachting sector, similarly to other branches of transportation, faces challenges stemming from global environmental regulations and a growing societal awareness of ecology. Conventional motor yachts powered by fossil fuels emit considerable amounts of carbon dioxide (CO_2), nitrogen oxides (NO_x), sulphur oxides (SO_x), and particulate matter. These pollutants adversely affect aquatic ecosystems and air quality, while even relatively small spills of fuel or lubricants in marinas accumulate in enclosed waters, causing disproportionate ecological harm. One of the key factors accelerating the transition is the implementation of international regulations limiting greenhouse gas emissions in shipping, such as the International Maritime Organization (IMO) norms and the European Green Deal strategy [12, 24].

Although motor yachts account for a relatively small share of overall maritime traffic, their environmental impact is increasingly scrutinised. Marinas are often located in sensitive coastal areas with high tourism activity, which amplifies the social visibility of environmental issues. The International Maritime Organization's Emission Reduction Strategy [24] sets out a long-term pathway for lowering greenhouse gas emissions in maritime transport. While its direct scope applies primarily to commercial vessels, the resulting regulatory environment exerts pressure on the recreational sector to adopt sustainable solutions. Likewise, the European Green Deal [12] and its associated initiatives emphasise the need to decarbonise all modes of transport, including leisure navigation, as part of broader climate goals.

In response to these challenges, yacht manufacturers and port-infrastructure operators increasingly invest in alternative propulsion solutions such as electricity and hydrogen. This transition is not without hurdles, however. Limited availability of charging and refuelling infrastructure, high implementation costs of new technologies, and the need to adapt current regulations to modern propulsion systems are only some of the aspects that require solutions [28]. Despite these difficulties, the decarbonisation trend in the yachting sector appears inevitable, with alternative energy sources playing a key role.

Contemporary propulsion technologies for motor yachts concentrate on two main approaches: electric energy and hydrogen. Both systems have benefits and challenges that influence their adoption in the yachting sector. Electric propulsion is currently one of the most rapidly developing solutions in recreational navigation. The use of lithium-ion batteries and the growing number of charging stations enable increasingly widespread deployment of electric craft. The key advantages include zero local emissions, quiet operation, and low operating costs as noted in conventional diesel yacht engine literature [54]. Nevertheless, limited range and long charging time are significant barriers, especially for vessels covering longer distances.

Hydrogen propulsion uses proton-exchange membrane fuel cells (PEMFC), which convert hydrogen into electrical energy, producing only water as a by-product. The technology allows for a substantially greater range than batteries, while hydrogen refuelling time is comparable to conventional petrol or diesel refuelling. The main challenges include the high costs of hydrogen production and storage, as well as the underdeveloped refuelling infrastructure in marinas. Both solutions underpin the decarbonisation of waterborne transport and can coexist as complementary technologies in the future – electric propulsion being optimal for shorter routes, while hydrogen will be used for long-distance voyages. Zaha Hadid Architects proposed the first design attempts into new marinas as NatPower H hydrogen refuelling stations, designed for 25 Italian marinas and ports (Fig. 1).

Fig. 1. Zaha Hadid architects reveals design for hydrogen refueling stations across the Italian marinas [46]

At the same time, the regulatory context is becoming increasingly complex. The IMO's Revised GHG Strategy, adopted in 2023, strengthened the ambition to achieve net-zero emissions from shipping by 2050, with intermediate milestones for 2030 and 2040. Although the strategy does not explicitly cover yachts, it provides an important political signal that all segments of maritime activity should contribute to decarbonisation. In Asia, national hydrogen strategies, particularly in Japan and South Korea, promote large-scale deployment of hydrogen infrastructure that also extends into recreational maritime applications. These policy frameworks create both opportunities and obligations for the yachting sector [35].

The environmental transition is not only a technical or regulatory matter but also an economic and social one. Unlike commercial shipping, motor yachts are luxury goods. Their owners and users are often motivated not only by functionality but also by reputation and lifestyle choices. Ecological awareness is becoming an element of social prestige, with yacht buyers increasingly seeking vessels that combine performance with environmental responsibility. As a result, marina operators who implement visible, sustainable solutions – such as solar canopies, floating photovoltaic platforms, or hydrogen refuelling barges – gain reputational advantages. This dimension is particularly relevant in tourist destinations, where environmental performance can directly influence customer satisfaction and regional image.

Digitalisation and "smart marina" concepts further accelerate the transition. Modern marinas integrate Internet of Things (IoT) devices, intelligent energy-management systems, and predictive maintenance tools. These allow optimisation of charging infrastructure, reduction of downtime, and enhancement of safety. Integration with renewable energy sources, such as solar modules on docks or small-scale wind turbines, supports energy autonomy. The deployment of hybrid solutions combining batteries and hydrogen storage illustrates the direction of innovation (Fig. 2).

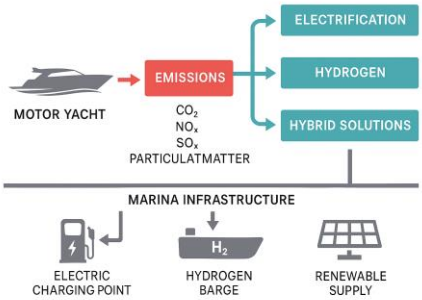

Fig. 2. Main sources of emissions in motor yachts and potential alternative energy pathways

The academic debate highlights that electricity and hydrogen will most likely coexist rather than compete. Electric propulsion is optimal for short-range and urban navigation, while hydrogen offers greater range and faster refuelling. Both require significant infrastructural investments, supportive regulation, and long-term environmental assessment. The gaps that remain include economic viability modelling, standardisation of hydrogen safety procedures in small ports, and behavioural analysis of yacht users.

The aim of this paper is therefore to examine alternative energy sources and modern fuel stations for motor yachts in a holistic manner. Specifically, the objectives are:

1. To provide an overview of the state of the art in electric and hydrogen propulsion for motor yachts, including comparative efficiency analysis
2. To assess the infrastructure requirements of modern fuel stations, with evaluation criteria derived from literature and expert consultations
3. To apply life-cycle cost (LCC), net present value (NPV), and return on investment (ROI) methods to economic feasibility
4. To model the environmental impacts of different station variants using life-cycle assessment (LCA)
5. To examine selected case studies in Europe, North America, and Asia, identifying best practices and architectural integration strategies.

The ultimate goal is to situate the recreational yachting sector within the broader energy transition of maritime transport, highlighting both opportunities and challenges. By emphasising infrastructure, economics, and consumer behaviour, this paper contributes to the ongoing discussion on sustainable mobility and coastal development.

2. Literature review and state of the art

2.1. Previous research on alternative energy sources in yachting

Research on alternative energy sources in waterborne transport has gained prominence in recent years, especially in the context of global climate goals. The literature on electric and hydrogen propulsion focuses primarily on energy efficiency, infrastructure barriers, and the costs of deployment. At the same time, studies on conventional diesel yacht engines remain an important reference point for assessing the transition towards low- and zero-emission systems [54]. While most research has historically focused on large-scale shipping, there is growing recognition that recreational craft also require sustainable solutions.

Electric propulsion systems today are applied mostly in smaller recreational craft. The main barrier to their wider diffusion in motor yachts remains the limited battery capacity and long charging time. Kolodziejski and Michalska-Pozoga [30] analysed battery energy storage systems in ships' hybrid and electric propulsion, pointing to their growing relevance for smaller vessels. Grey and Hall [17] projected that technological progress in lithium-ion batteries – particularly advances toward solid-state batteries – may significantly increase the range of electric vessels in the next decade (Fig. 3).

Fig. 3. Aqua superPower charging station for small vessels [45]

By contrast, hydrogen technology is currently applied predominantly in larger vessels and demonstration projects. Proton-exchange membrane fuel cells (PEMFC) are considered the most promising solution for marine use, due to their relatively high energy efficiency and compact size. Van Biert et al. [7] reviewed marine fuel-cell systems, highlighting their potential for zero-emission operation but also the high costs of hydrogen production and infrastructure.

Recent comparative analyses of hydrogen production methods confirm that the environmental impact of hydrogen depends strongly on the energy source used in electrolysis. Ji and Wang demonstrated that only hydrogen produced from renewable electricity ("green hydrogen") offers genuine decarbonisation potential. This distinction is critical when evaluating hydrogen's role in yachting.

Several demonstration projects provide empirical evidence. In Norway, fuel-cell ferries and hybrid yachts are part of a broader national hydrogen strategy. In the Netherlands, research programmes combine urban mobility, inland waterways, and recreational boating in pilot projects. In Japan and South Korea, hydrogen and electric yachts are integrated into national "green port" strategies [29].

Table 1. Comparison of the basic parameters of electric and hydrogen propulsion

Parameter	Electric propulsion	Hydrogen propulsion
Range	150–300 km	400–600 km
Charging/refuelling time	60–120 min	5–10 min
CO_2 emissions	0 g/km (with RES)	0 g/km (with RES)
Infrastructure cost	Low	High

These data suggest that electric propulsion will be optimal for coastal and short-range navigation, whereas hydrogen will be preferable in long-range and more commercial applications (Fig. 4).

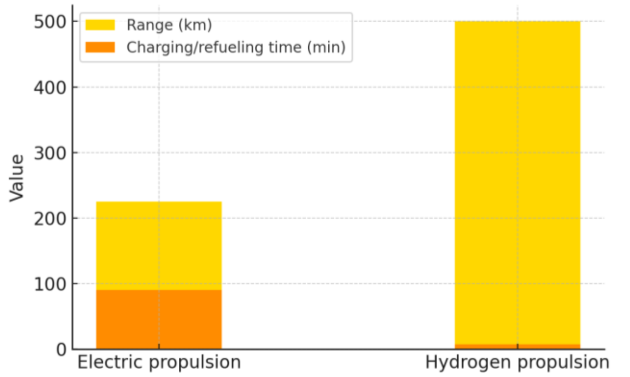

Fig. 4. Comparison of charging/refuelling time for electric and hydrogen propulsion

2.2. Additional comparative research

To complement the existing findings, new studies have introduced multidimensional frameworks for evaluating propulsion technologies. Bouman et al. [38] emphasised the importance of integrating greenhouse gas reduction measures across all shipping sectors, while Balcombe et al. [9] highlighted the role of policy in accelerating adoption of low-carbon fuels.

Table 2. Selected research themes on alternative propulsion in yachting

Author(s)	Technology	Focus	Key Findings
Kolodziejski & Michalska-Pozoga (2023) [30]	Electric batteries	Hybrid/electric propulsion	Batteries feasible for small vessels, limited by range
Grey & Hall (2020) [17]	Lithium-ion, solid-state	Technological outlook	Solid-state batteries may revolutionise vessel range
Van Biert et al. (2016) [7]	Fuel cells	Maritime applications	PEMFC promising, infrastructure costly
Ji & Wang (2021) [28]	Hydrogen	Production methods	Green hydrogen essential for sustainability
Kim et al. (2022) [29]	Hydrogen + electric	Port infrastructure	Hybrid systems feasible, supported by policy
Balcombe et al. (2019) [9]	Multi-fuel	Policy and technology	Electricity + hydrogen will coexist in future transport

This body of literature demonstrates that while both electricity and hydrogen are being developed, research often treats them in isolation. Comparative studies specific to yachting remain relatively scarce, leaving room for further integrated analysis.

2.3. Comparative efficiency of propulsion technologies

When comparing electric and hydrogen propulsion, assessments must include not only range, CO_2 emissions, and refuelling/charging time, but also infrastructure requirements, life-cycle costs, and safety considerations [2]. Electric propulsion is generally more cost-effective and better suited to small craft, whereas hydrogen offers longer range and shorter refuelling times but requires significantly higher capital investment. Life-cycle assessments confirm that electric yachts powered by renewable energy have the lowest carbon footprint, but hydrogen offers higher scalability for long-range applications [9].

Table 3. Efficiency of different fuel-cell types in maritime applications

Fuel-cell type	Efficiency (%)	Advantages	Drawbacks
PEMFC	40–60	Compact, quick start	Sensitive to impurities, costly catalysts
SOFC	50–65	High efficiency, fuel flexibility	Slow start-up, high temperature
AFC	50–60	High performance with pure H_2	Sensitive to CO_2 contamination
Abbreviations: PEMFC – Proton Exchange Membrane Fuel Cell; SOFC – Solid Oxide Fuel Cell; AFC – Alkaline Fuel Cell			

Balcombe argues that both electricity and hydrogen will play complementary roles. The efficiency of each depends on vessel size, operational profile, and infrastructure context. DNV's *Maritime Forecast to 2050* [11] projects that both battery-electric and hydrogen-fuelled vessels will gain significant shares of the maritime market. In addition to propulsion efficiency, safety remains a decisive factor. Hydrogen storage at 350–700 bar requires advanced safety systems and regulatory approval, while electric batteries pose risks of thermal runaway [5]. Both technologies demand tailored safety frameworks for marinas. Finally, market projections suggest that battery costs will continue to decline, while green hydrogen costs are expected to decrease significantly by 2030 due to scaling and renewable expansion [23, 43] (Fig. 5).

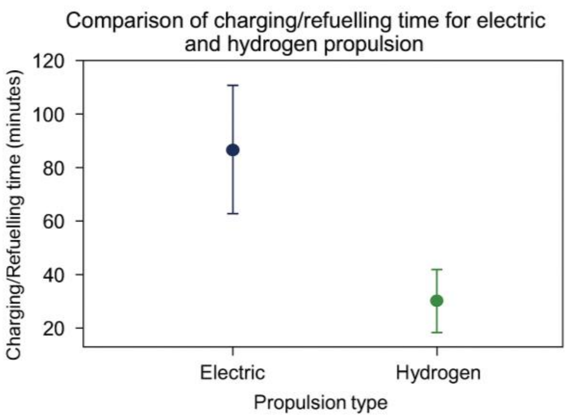

Fig. 5. Comparative efficiency of electric vs hydrogen propulsion

3. Research methodology

3.1. Evaluation criteria for alternative fuel stations infrastructure

The objective of the analysis of modern fuel stations for motor yachts is to determine their suitability within the energy transition of recreational navigation. The infrastructure supporting alternative energy sources – electricity and hydrogen – was assessed. The key criteria included availability, energy efficiency, operational safety, and compliance with environmental regulations. A qualitative indicator method was applied based on a weighted scoring matrix, with weights derived from literature analysis and consultations with industry experts. Port accessibility and technical feasibility of implementing the infrastructure in existing marinas were also considered [10].

Table 5. Weights assigned to the evaluation criteria

Criteria	Description	Weight (%)
Availability	Number of charging/refuelling points on a given waterbody	30
Energy efficiency	Average conversion and transmission losses	25
Operational safety	Risk of failure and compliance with technical standards	20
Regulatory compliance	Compliance with EU and IMO environmental regulations	15
Integration with infrastructure	Applicability in existing marinas without major changes	10

The sum of weights equals 100%, and the final score for a given station was calculated as a weighted average according to the above distribution [10].

Table 6. Extended evaluation criteria with additional socio-economic indicators

Criterion	Description	Weight (%)
Social acceptance	User perceptions and willingness to adopt technology	10
Economic incentives	Availability of subsidies, grants, or tax relief	8
Aesthetic integration	Visual compatibility with marina architecture	7
Life-cycle adaptability	Flexibility to incorporate future technologies	5

These added indicators reflect the importance of social, economic, and architectural dimensions in marina planning.

3.2. Methods for economic efficiency analysis

The economic efficiency of alternative fuel stations was evaluated using the Life-Cycle Costing (LCC) methodology, enabling a comprehensive assessment of capital expenditures, operating costs, and environmental costs over the entire life cycle of the investment. Additionally, Net Present Value (NPV) and Return on Investment (ROI) were used to assess the profitability of modernisation projects and construction of new facilities [19].

Table 7. Example input data for LCC analysis for electric and hydrogen stations

Parameter	Electric station	Hydrogen station
Capital cost [million EUR]	0.45	1.25
Annual operating cost [EUR]	15,000	30,000
Service life [years]	20	20
Residual value [million EUR]	0.05	0.10

NPV and ROI were calculated for three scenarios – conservative, realistic, and optimistic – considering discount rates from 3% to 7% [19].

Table 8. Comparative LCC outcomes for electric vs hydrogen stations under different scenarios (new)

Scenario	Electric station NPV [M€]	Hydrogen station NPV [M€]	ROI (Electric)	ROI (Hydrogen)
Conservative (7%)	0.12	–0.30	6%	–2%
Realistic (5%)	0.25	–0.05	11%	1%
Optimistic (3%)	0.40	0.20	18%	7%

The analysis demonstrates that economic feasibility strongly depends on the discount rate and subsidy availability. Electric stations show higher resilience across scenarios.

3.3. Environmental impact modelling of modern fuel stations

Environmental impacts were analysed using a Life Cycle Assessment (LCA) model that considered greenhouse gas emissions, primary energy consumption, and potential impacts on aquatic ecosystems. Input data originated from real-world analyses of fuel stations in Europe and from peer-reviewed literature. Modelling was conducted for three infrastructure variants: electricity-only, hydrogen-only, and hybrid [6].

Table 9. Comparative LCA outcomes for different station types

Variant	CO_2 emissions [kg CO_2-eq/yr]	Primary energy demand [MWh/yr]	Aquatic impact score (0–100)
Electric (RES supply)	2100	11.5	10
Hydrogen (grey)	8700	32.0	40
Hydrogen (green)	3000	14.2	12
Hybrid	3500	16.0	15

Results confirm that green electricity is the lowest-impact pathway, but hydrogen from renewables also offers competitive reductions compared to fossil-fuel baselines [34].

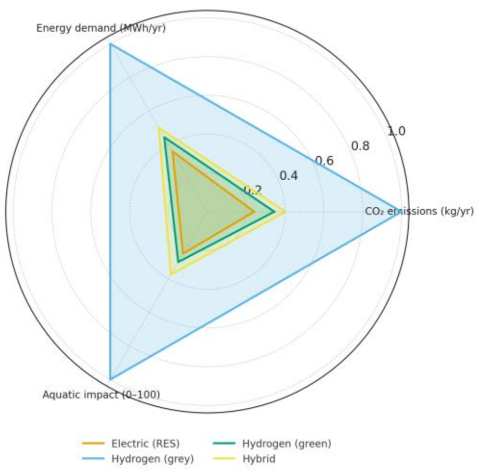

Fig. 6. Comparative LCA impact of electric, hydrogen, and hybrid stations (new)

In addition to environmental indicators, modelling also took into account compliance with international safety and design standards. The ISO 19880-1:2020 guidelines for hydrogen fuelling stations provide the fundamental framework for assessing risks and ensuring the safe integration of hydrogen technology in marina environments [22].

Radar chart showing three categories (CO_2 emissions, energy demand, aquatic impact), with four variants compared in proportional scales.

4. Characteristics of alternative energy sources

4.1. Electrical energy: batteries and charging systems

The application of electricity in motor-yacht propulsion depends primarily on advances in energy storage and charging infrastructure. The key component is the lithium-ion (Li-ion) battery, which provides favourable energy density and a relatively long lifetime. Lithium-iron-phosphate ($LiFePO_4$) batteries are increasingly popular due to their high chemical stability and operational safety.

Table 10. Comparison of battery technologies

Battery type	Energy density [Wh/kg]	Cycle life [cycles]	Charging time	Advantages
Lithium-ion	150–250	1000–3000	4–8 h	Good availability; high energy density
$LiFePO_4$	90–140	2000–7000	4–6 h	High durability; safer chemistry
Solid-state (SSB)	300–500 (forecast)	> 5000 (forecast)	< 2 h (forecast)	High-efficiency potential

Recent technological progress includes:

- Solid-state batteries (SSBs), which are expected to improve energy density, lifespan, and safety significantly [26]
- Second-life battery use, where automotive Li-ion batteries are repurposed for marine storage applications, reducing costs and environmental impact [8]
- High-power DC fast charging, already piloted in Norway and the Netherlands, reduces charging times below one hour [33].

Charging infrastructure is developing in parallel, from standard marina AC chargers to high-power DC systems and wireless solutions. Ports increasingly implement fast-charge stations that can reduce charging times to one hour or less [32]. “We are thrilled to lead the charge in embracing Aqua SuperPower’s revolutionary marine fast charge network, positioning Marina di Stabia as a vanguard of sustainable boating practices in the Gulf of Naples,” said Salvatore La Mura, Marina Manager at Marina di Stabia.

Fig. 7. Example of a modern marina with integrated electric charging systems [51]

Table 11. Classification of charging systems for yachts

System type	Power range [kW]	Typical location	Pros	Cons
AC standard	11–22	Small marinas	Low cost, easy installation	Slow charging
DC fast	50–350	Commercial ports	Very fast charging	Requires advanced cooling, grid impact
Inductive wireless	10–50	Premium marinas	High convenience	Lower efficiency, higher cost
Mobile charging barges	100–200	Urban waterfronts	Flexible deployment	Logistics complexity

4.2. Hydrogen: storage and applications in a yacht propulsion

Hydrogen as an alternative fuel is primarily used in proton-exchange membrane (PEM) fuel cells, characterised by high energy efficiency and zero local emissions. The main challenge for hydrogen remains its storage and distribution [1].

Table 12. Hydrogen storage forms and characteristics

Storage form	Pressure/ temperature	Typical application	Advantages	Drawbacks
Compressed (gaseous)	350–700 bar	Mobile tanks	Mature technology	High pressure; safety systems required
Liquefied (cryogenic)	−253°C	Stationary applications	Higher volumetric energy density	High cooling costs; boil-off losses
Chemical (e.g., hydrides)	Depends on the compound	Experimental	Potential for long-term storage	Complex recovery; mass penalties

Several innovations are being tested:

- On-site hydrogen generation using electrolysers integrated with marina PV systems [15]
- Liquid organic hydrogen carriers (LOHCs) that allow for safer transport of hydrogen at ambient conditions [39]
- Mobile hydrogen refuelling barges, considered in the Netherlands, offer flexibility in seasonal yachting destinations [44].

5. Modern fuel stations for motor yachts

5.1. Electric charging stations: challenges and prospects

The development of charging infrastructure for electric recreational craft is a key element of decarbonising the yachting sector. Current solutions vary in power, charging method, and integration with existing port infrastructure. The most common are AC chargers rated 11–22 kW, but in commercial ports and larger marinas, DC stations of 50–150 kW are increasingly installed. Inductive (wireless) charging systems also offer high operational convenience, eliminating the need to connect cables. Implementing such technologies requires adapting quay infrastructure and equipping vessels to receive power from wireless platforms [36].

Table 6. Types of electric charging stations

Station type	Power [kW]	Supply	Average charging time	Notes
AC standard	11–22	AC	4–8 h	Common, slow charging
DC fast	50–150	DC	1–2 h	Requires cooling and supervision
Inductive	10–50	Wireless	1.5–3 h	High convenience; lower power

From an infrastructural perspective, the most significant challenges include:

- Grid capacity limits, particularly in tourist-heavy coastal areas
- Investment costs, especially when installing DC or wireless stations
- Standardisation issues arise as different manufacturers propose non-harmonised connectors and charging protocols [21].

Future developments point to megawatt charging systems (MCS), which could allow fast charging even for large passenger vessels, and hybrid marina systems, where charging is supported by on-site energy storage to stabilise local grids [18].

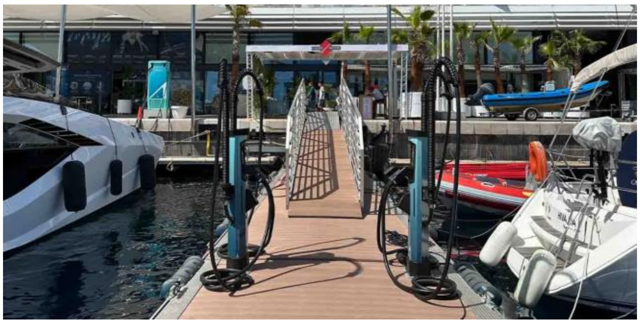

Fig. 8. Example of a modern marina integrating fast DC charging for yachts at the Yacht Club de Monaco [50]

5.2. Hydrogen refuelling stations: technical requirements and safety

Hydrogen stations for recreational navigation pose new challenges for design and operations. They require specialist tanks and compressors as well as adherence to stringent safety standards and regulations governing pressure systems. A typical hydrogen refuelling station comprises a storage tank, compression system, and dispensing module. In marinas, mobile solutions are most frequently considered – barges or trailer-mounted units that can be moved between locations depending on demand [3].

Table 7. Technical requirements for hydrogen stations

Infrastructure element	Characteristic
Refuelling pressure	350–700 bar
Safety systems	Leak detection, ventilation, relief, and shut-off valves
Location requirements	Setbacks from buildings, signage, and monitoring
Mobile variants	Barges or containerised trailer solutions

Although the capital cost of hydrogen stations remains high, pilot projects in Norway, Germany, and the Netherlands have demonstrated technical feasibility and growing user acceptance. Their implementation in marinas requires environmental permits, risk assessments, and routine inspections to ensure compliance with ISO and IMO regulations [25].

6. Results analysis and case studies

6.1. Modern fuel stations in Europe

Europe is at the forefront of implementing alternative-fuel infrastructure for navigation, not only due to technological capabilities but also thanks to a robust political framework that encourages sustainable development. EU directives, Green Deal policies, and IMO requirements have pushed many countries to test solutions that integrate energy transition with marina architecture.

The Ulsteinvik marina (Norway) stands as a milestone in hydrogen refuelling for recreational yachts. Its architectural concept is particularly innovative because the design deliberately reduces the perception of industrial infrastructure. The use of glulam timber beams creates a natural and regionally contextual character, while expansive glass façades provide both natural light and a visual connection with the fjord. From a technical perspective, the station includes mobile hydrogen tanks and modular compressors, which allow for scalability depending on seasonal demand. Socially, the station has been widely accepted by the local community, partly because it has been presented as both a functional facility and a public meeting place with educational content about renewable energy (Fig. 9).

Fig. 9. Ulsteinvik marina with integrated hydrogen refuelling station [47]

The Port of Bergen (Norway) is another leading example, but here the focus lies on electricity rather than hydrogen. The hybrid station combines AC slow chargers for smaller yachts with DC fast chargers for larger vessels. A distinctive element is the use of hydropower, which makes the energy cycle almost completely carbon neutral. The architecture of the technical enclosures has been deliberately minimised; small modular pavilions with green roofs integrate visually with the waterfront and even serve ecological functions, such as providing habitats for insects and retaining rainwater. From an operational perspective, the port authority emphasises that the modularity of the infrastructure allows for quick replacement and future upgrades, reducing life-cycle costs [37] (Fig. 10).

Fig. 10. A ship using Zinus Cruiser charger in the Port of Bergen [47]

In Amsterdam (Netherlands), space constraints in the densely built waterfront have inspired highly flexible solutions. The city has introduced several DC fast-charging points that can be accessed by both commercial and recreational craft. However, the most innovative element is the mobile hydrogen-barge concept, a floating refuelling unit that can move between districts depending on seasonal demand. This model not only reduces the need for permanent onshore facilities but also offers a scalable and transferable solution that could be replicated in other urban ports worldwide. Amsterdam's approach demonstrates how limited urban space can be optimised through mobile, modular energy infrastructure, which reduces environmental impact while supporting economic activity in water tourism [14] (Fig. 11).

Fig. 11. Amsterdam marina with DC charging points and mobile hydrogen barge concept [53]

6.2. Development of alternative fuel infrastructure in North America

In North America, the transition towards alternative energy in marinas is driven by both environmental policies and the private sector's interest in branding marinas as sustainable tourism hubs. Particularly in the United States and Canada, public–private partnerships have proven crucial in financing and scaling projects.

Marina del Rey (California, USA) illustrates how energy infrastructure can serve as a symbol of innovation. The installation of solar PV canopies with integrated DC fast chargers has not only decarbonised local yachting but also created a new architectural landmark. The wave-inspired design of the canopies echoes the maritime identity of the marina, blending aesthetics with function. From a technological perspective, the integration of a 500 kWh energy storage system ensures grid stability, which is crucial given the high power demand of simultaneous yacht charging. The marina has become a tourist attraction in its own right, often featured in media as an example of green port design [42] (Fig. 12).

Fig. 12. Marina del Rey with PV-integrated fast-charging canopies [52]

In the Great Lakes region, the *Clean Ports Project* has implemented stations in Chicago and Cleveland that are technologically simpler but socially significant. Floating pontoons with charging units represent a climate-resilient solution, able to adapt to fluctuating water levels caused by seasonal variations and climate change. Construction materials such as wood, composite panels, and anodised aluminium combine resilience with modern aesthetics. Importantly, local stakeholders – including yacht clubs and municipalities – have expressed support because the stations enable new eco-tourism initiatives, including "green regattas" and sustainable water sports [16].

In British Columbia (Canada), the flagship Vancouver project focuses on hydrogen. What makes it exceptional is the integration of local electrolysis units powered by hydropower. This enables full autonomy, avoiding the logistical challenges of hydrogen delivery. The design also includes public walkways and observation decks, allowing visitors to observe the hydrogen production process. This educational component is intended to build trust and social acceptance, countering scepticism often associated with hydrogen storage. By combining infrastructure with public outreach, the project is reshaping perceptions of hydrogen as a safe and sustainable fuel (Fig. 13).

Fig. 13. Vancouver marina project with on-site hydrogen electrolysis station [48]

6.3. Asian innovations in sustainable yachting

In Asia, rapid urbanisation and high population density create unique challenges, but also foster bold experiments with compact, multifunctional infrastructure. Japan and South Korea are currently at the forefront of marina innovation.

In Yokohama (Japan), the automated electric charging station combines AC slow charging for overnight berthing with DC fast charging for day users. Its defining feature is the digital reservation system, integrated into a mobile application that manages marina traffic and energy use. Architecturally, the use of translucent PV roofs allows the structures to blend into the urban waterfront while providing shading and energy generation. The facility is also connected to a district energy management system, ensuring that surplus electricity can be redistributed within the city grid. Yokohama thus demonstrates how a marina can function not only as a transport hub but also as an active node in a smart city energy network [27] (Fig. 14).

Fig. 14. Yokohama marina with translucent PV-integrated charging canopy [49]

The Busan EcoPort (South Korea) pilots hydrogen refuelling in combination with automated berthing systems, where digital sensors guide yachts to align precisely with refuelling arms. This reduces human error and enhances safety. Architecturally, the project features a glazed hydrogen pavilion with educational and exhibition spaces, as well as a public viewing terrace overlooking the bay. By combining infrastructure with cultural and social functions, Busan EcoPort transforms a purely technical facility into a civic attraction.

Moreover, South Korea's Blue Marina initiative envisions ten hybrid marinas, each equipped with both hydrogen and electric charging facilities. This program is directly supported by the Korea Energy Agency, reflecting the country's strategic commitment to marine decarbonisation. Importantly, the program also includes training for marina personnel and awareness campaigns for yacht owners, ensuring that the technological transformation is matched by social readiness [229].

6.4. Comparative global overview

The case studies analysed above highlight distinct regional approaches to marina decarbonisation:

– Europe focuses on contextual design and hybridisation, ensuring that energy infrastructure blends with cultural landscapes while offering flexibility (Ulsteinvik, Bergen, Amsterdam)
– North America prioritises large-scale integration and resilience, with emphasis on grid stability, floating solutions, and hydrogen autonomy (Marina del Rey, Great Lakes, Vancouver)

– Asia pushes towards automation, multifunctionality, and urban integration, embedding marinas into wider smart-city systems (Yokohama, Busan).

The comparative analysis suggests that while all regions share the common goal of decarbonisation, their approaches differ depending on geography, cultural context, and economic structure.

7. Conclusions and future directions

7.1. Potential innovations in refuelling technology

The analysis of alternative energy infrastructure for motor yachts highlights a range of innovations that are likely to reshape the yachting sector in the near and medium term. Both electricity-based systems and hydrogen-based technologies are developing rapidly, but future advancements are expected to move beyond current limitations [41].

One of the most promising directions is the development of high-power wireless inductive charging systems. Unlike conventional plug-in technologies, inductive charging eliminates the need for manual connection of cables, which is often cumbersome and poses safety risks in humid marina environments. Pilot projects in Norway and Japan demonstrate that inductive pads embedded in pontoons or quay walls can enable automatic power transfer at capacities exceeding 100 kW. Once commercialised, such systems could support short-term docking, where vessels recharge opportunistically during passenger embarkation or provisioning.

Another significant innovation is the emergence of containerised hydrogen stations. These are modular units integrating storage tanks, compressors, and dispensing modules in compact, relocatable containers [31]. Some prototypes include on-board electrolysers, allowing local production of green hydrogen from renewable sources such as photovoltaic panels or small-scale wind turbines. The decentralisation of hydrogen production would reduce reliance on large-scale logistics chains, which remain a bottleneck for maritime decarbonisation. Containerised stations could be deployed seasonally or in response to tourism intensity, ensuring both flexibility and cost-effectiveness [4].

Fig. 15. Conceptual rendering of a hybrid marina integrating electric, hydrogen, and renewable energy systems

Hybridisation of energy sources is another direction. Combining batteries, hydrogen, and renewable generation (PV, wind, wave energy) in a single marina could increase resilience and reduce operating costs. Smart microgrids capable of balancing supply and demand in real time are being tested in ports in Germany and South Korea. Such systems may evolve into autonomous energy hubs, serving not only yachts but also adjacent urban districts.

Architecturally, marina infrastructure will increasingly integrate energy technologies into landscape and design concepts. Green roofs, façade-integrated photovoltaics, and floating structures are no longer optional but essential in reconciling environmental performance with aesthetic quality. Future marinas will likely be conceived not just as refuelling points but as multifunctional civic spaces – combining leisure, education, and sustainability.

7.2. Development prospects and possible investment directions

From an investment perspective, the development of alternative-fuel marinas presents both opportunities and challenges.

Regulatory and policy context

The EU's Fit for 55 package, IMO emission strategies, and North American clean port initiatives provide a strong regulatory framework. Public subsidies, green transition funds, and private venture capital are already supporting pilot projects. However, a lack of standardised technical norms remains a barrier. International harmonisation of pressure standards for hydrogen refuelling (350 vs 700 bar), as well as universal charging protocols for electric vessels, will be critical for scaling infrastructure globally [20].

Economic efficiency and return on investment

Life-cycle cost analyses indicate that while electric charging stations offer lower capital costs and shorter payback periods, hydrogen infrastructure may deliver higher long-term returns in marinas with heavy traffic and larger vessels. For investors, the most promising business models combine user fees, public subsidies, and ancillary services such as renewable energy sales to adjacent urban grids [13].

Strategic locations for investments

The analysis of global case studies suggests that the most promising investment locations include:

– Tourist-intensive coastal regions (Mediterranean, Caribbean), where demand is seasonal but concentrated
– Urban waterfronts (Amsterdam, Vancouver, Yokohama), where marinas form part of broader smart-city strategies
– Climate-sensitive inland waterways (Great Lakes, Danube), where floating modular infrastructure provides resilience.

Social and cultural dimensions

The success of alternative fuel marinas depends not only on technology but also on user acceptance. Hydrogen, in particular, faces public scepticism linked to perceived safety risks. Educational pavilions, transparent design, and public outreach programmes – as demonstrated in Busan and Vancouver – are crucial in building trust. Future marinas will likely serve as demonstration spaces for sustainable living, influencing not only yacht owners but also local communities and tourists.

Long-term perspectives

In the longer term, the integration of marinas into blue economy strategies will be vital. Alternative energy marinas can become nodes of broader coastal development policies, supporting renewable energy production, eco-tourism, and urban resilience. By 2050, it is plausible that zero-emission marinas will form part of international environmental certifications, similar to today's Blue Flag programme but focused on energy sustainability [13, 40].

7.3. Achieved goals and original contribution

This article achieved its goals by:

1. Systematically reviewing alternative propulsion technologies for yachts and their infrastructural requirements
2. Proposing an original evaluation framework (weighted indicators)
3. Applying LCC and LCA methodologies to assess economic and environmental feasibility
4. Conducting comparative case studies from three continents
5. Developing conceptual diagrams and visualisations integrating engineering and architectural perspectives.

The originality of this study lies in its integrative perspective. For the first time, the technical–economic assessment of alternative fuel stations for motor yachts has been systematically combined with architectural and social dimensions of marina development. While most existing studies address engineering feasibility or environmental performance in isolation, this article introduces a holistic evaluation framework that incorporates weighted indicators, life-cycle costing (LCC), and life-cycle assessment (LCA), alongside aesthetic, spatial, and user-related criteria.

Another innovative contribution is the use of conceptual diagrams and visual renderings as part of the methodological approach. These visualisations are not only illustrative but also serve as tools for design integration and stakeholder communication, enabling decision-makers, architects, and engineers to align technical requirements with urban and landscape contexts. In this sense, the paper moves beyond a descriptive review of state-of-the-art technologies and proposes an original model for assessing and planning sustainable marina infrastructure.

By bridging technical, economic, and architectural perspectives, the study highlights the potential for marinas to act not only as energy nodes but also as civic and cultural spaces. This dual function reflects a novel paradigm for the decarbonisation of recreational navigation, positioning marina design at the intersection of engineering innovation and socio-spatial development.

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